



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**PERFORMANCE ANALYSIS OF IEEE 802.11A SIGNALS
UNDER DIFFERENT OPERATIONAL ENVIRONMENTS**

by

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September 2004

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**PERFORMANCE ANALYSIS OF IEEE 802.11A SIGNALS UNDER DIFFERENT
OPERATIONAL ENVIRONMENTS**

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ABSTRACT

With the rapid employment of wireless networks commercially, the military is seeking viable solutions for providing high-speed wireless network throughout the battle space. The IEEE 802.11a wireless LAN presents an attractive solution, providing up to 54 Mbps of data-link bandwidth. Moreover, it operates in the less congested 5-GHz U-NII band and possesses more operating channels.

This research implemented two prototype systems using low-cost commercially available hardware. The Cisco Aironet 1400 wireless bridge and the Proxim Tsunami MP.11a wireless system were chosen for their superior specifications and for their reputation of being market leaders in IEEE 802.11 wireless products. The performances of the prototype systems were evaluated in three operational environments (land, water and vegetation). The data collected were then compared to the theoretical performance.

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LIST OF SYMBOLS, ACRONYMS, AND/OR ABBREVIATIONS

AES	Advanced Encryption System
AP	Access Point
APC	Armor Personnel Carrier
BCC	Binary Convolutional Code
BPSK	Binary Phase Shift Keying
BSU	Base Station Unit
CCK	Complementary Code Keying
CDMA	Code Division Multiple Access
COFDM	Coded OFDM
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Committee
FFT	Fast Fourier Transform
GUI	Graphical User Interface
ISM	Industrial, Scientific and Medical
LAN	Local Area Network
LLC	Logical Link Control
LOS	Line-of-Sight
MAC	Medium Access Control
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PBCC	Packet Binary Convolutional Coding

PHY	Physical
PPDU	Physical-Layer Convergence Procedure Protocol Data Unit
PSDU	Physical-Layer Service Data Unit
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAM	Random Access Memory
RC4	Rivest Cipher 4
RSN	Robust Security Network
RSSI	Received Signal Strength Indicator
SU	Subscriber Unit
TKIP	Temporal Key Integrity Protocol
UAV	Unmanned Aerial Vehicle
U-NII	Unlicensed National Information Infrastructure
VLSI	Very Large Scale Integrated circuit
WEP	Wired Equivalent Privacy
WPA	Wi-Fi Protected Access

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EXECUTIVE SUMMARY

With the rapid commercial advancement and deployment of wireless LAN, over the past decade, high-speed wireless LANs have become a viable option for the military. Not only has the technology matured, it has also become affordable due to mass production. The wireless LAN provides three main features that are vital for military deployment – mobility, ease of deployment, and flexibility. This research implemented two prototype systems using commercially available low-cost hardware. The performances of these prototype systems were evaluated in three operational environments. The data collected were then compared to the theoretical performance.

The objectives of this research are to answer the following questions:

- What specific commercially available low-cost hardware can be used to implement an IEEE 802.11a network outdoors?
- What is the performance capability of the hardware under various operational environments?
- How can the use of directional antennas improve the performance capability of an IEEE 802.11a network outdoors?

The first question was answered by implementing IEEE 802.11a networks, using commercially available low-cost hardware developed by Cisco and Proxim. Cisco and Proxim were chosen because they are market leaders in IEEE 802.11 wireless equipment and their product specifications are superior. The breakdown of the prototype systems and their cost are shown in Table 1 below.

Hardware	Quantity	Total Price
Dell Latitude C840	1	US\$2,000
Sony VAIO	1	US\$2,000
Cisco Aironet 1400 Series Wireless Bridge	2	US\$6,690
Proxim Tsunami MP.11a Wireless System	1 set	US\$2,400
Xantrex Power Supply	2	US\$500
Total Price of Hardware		US\$13,590

Table 1. Prototype Hardware Cost

To answer the second question, the prototype systems were tested under the following three operational environments:

- Land (Area surrounding NPS with LOS)
- Water (Along the coast of Monterey Bay)
- Vegetation (Hills of La Mesa Housing)

From the performance data collected, the maximum range recorded for land, water and vegetation are shown in Tables 2 and 3.

Operational Environment	Maximum Range Recorded at Data-link Rate of 54 Mbps
Land	3,000m
Water	1,750m
Vegetation	75m

Table 2. Cisco Aironet 1400 Wireless Bridge

Operational Environment	Maximum Range Recorded at a Optimal Data-link Rate of 36 Mbps
Land	2,350m
Water	250m
Vegetation	75m

Table 3. Proxim Tsunami MP.11a Wireless System

Test points that deviated from the LOS path resulted in a total loss of signal (i.e., IEEE 802.11a signals require LOS). The average data throughputs for the respective data-link rates are summarized in Table 4. This was based on the best data throughput obtained in vegetation. The optimal data-link rate for the Proxim Tsunami MP.11a wireless system was 36 Mbps. At the data-link rates of 48 and 54 Mbps, the data throughput was low with a very high packet error rate. Generally, file transfer was not successful.

Data-link Rate (Mbps)	Average Data Throughputs (Mbps)	
	Cisco	Proxim
6	2.70	2.79
9	4.92	5.27
12	5.75	5.82
28	8.65	8.33
24	10.61	9.41
36	14.70	10.65
48	19.50	-
54	20.62	-

Table 4. Data-link Rate versus Average Data Throughputs (In Vegetation)

For both prototype systems, use of encryption (WEP or AES) had negligible effect on the data. The use of a longer packet in the Cisco Aironet 1400 wireless bridge resulted in higher packet error rate. Despite this, the data throughput was not affected, as each packet was capable of transferring more data bits for the same overhead. It was also observed in both systems that data throughput decreased and the packet error rate increased with increasing range. The receiver sensitivity for the Cisco Aironet 1400 wire

less bridge was determined to be approximately 5 dB less than its specifications. The receiver sensitivity for the Proxim Tsunami MP.11a wireless system was in accordance with its specifications.

Finally, all tests were performed using directional antennas. The range performance increased significantly over the omni-directional antenna. The performance data for omni-directional antenna can be found in Maj. Goh Chee Seng's thesis [1].

The performance data collected in this research showed that IEEE 802.11a network is a viable solution for the military as a high-speed LAN. Despite their range limitation, IEEE 802.11a networks have more system capacity (eight channels compared to three for IEEE 802.11g) and occupy a less congested frequency band (5 GHz compared to 2.4 GHz). The range limitation can be overcome by designing the wireless LAN around the Standard Operating Procedure (SOP).

For example, in the case of armor infantry, the access points can be used on the Armor Personnel Carrier (APC), where troops are likely to be within 100 m of the APC. As for APC to APC links or APC to Unmanned Aerial Vehicle (UAV) links, a higher gain adaptive antenna could be used. Similarly for the Navy, higher gain adaptive antenna could be used to bridge the distance or the data-link rate could be compromised for distance.

I. INTRODUCTION

A. PURPOSE AND BENEFIT OF RESEARCH

The Internet has revolutionized the way information is exchanged throughout the world. A simple click of the mouse sends an email to a friend on the other side of the world within seconds. If this same speed of communication were available for military commanders, they would have an advantage over their adversaries. However, in the past, this was only possible when commanders had access through a wired Ethernet port.

Over the past decade, the rapid commercial advancement and deployment of wireless LANs made high-speed wireless LANs a viable option to the military. Not only has the technology matured, it has also become affordable due to mass production. The wireless LAN provides three main features that are vital for military deployment – mobility, ease of deployment, and flexibility. This research implemented two prototype systems using commercially available low-cost hardware. The performances of these prototype systems were evaluated under three operational environments. The data collected were then compared to the theoretical performance.

The objectives of this research were to answer the following questions:

- What specific commercially available low-cost hardware can be used to implement an IEEE 802.11a network outdoors?
- What is the performance capability of the hardware under various operational environments?
- How can the use of directional antennas improve the performance capability of an IEEE 802.11a network outdoors?

B. THESIS ORGANIZATION

Chapter II and III provide the background knowledge to understand the discussion presented in this research.

Chapter II provides an overview of the IEEE 802.11 standards and related security features (Wired Equivalent Privacy, WEP and Wi-Fi Protected Access, WPA).

Chapter III discusses the IEEE 802.11a standard, which includes key parameters of the standard, as well as the composition and functions of the MAC and PHY layer.

Chapter IV provides the specifications of the prototype systems, as well as the supporting software and hardware used in actual field-testing.

Chapter V covers the laboratory setup and testing, the test plans for all three operational environments, and the performance data collected for the Cisco Aironet 1400 wireless bridge.

Chapter VI covers the laboratory setup and testing, and the performance data collected for the Proxim Tsunami MP.11a wireless system.

Chapter VII summarizes this research and recommends future research.

C. PREVIOUS WORK

The performance data collected in this research will assist military commanders in making decisions on what WLAN to deploy for the military. Current research of the performance of the IEEE 802.11a network in an outdoor environment is very limited, as most commercial products are geared toward indoor environments. Recently, more outdoor IEEE 802.11a products have emerged in the market. They are mainly for bridging between two points. However, as most of these bridges have point-to-multipoint capability, they can perform the role of an Access Point (AP).

Maj. Goh Che Seng conducted detailed research into IEEE 802.11a signals, using APs with omni-directional antenna. From his research, it was shown that IEEE 802.11a signals needed LOS and did not perform well beyond 700 ft, a distance at which the data-link rate falls to less than half of the original 54 Mbps [1].

Cpt. Walter N. Currier Jr. carried out a similar study on the performance of IEEE 802.11b signals. His research determined that IEEE 802.11b signal propagation could be modeled against the two-rays or free-space propagation models [2]. Despite the longer-range capability of IEEE 802.11b signals, IEEE 802.11b has smaller system capacity and is expected to face more interference when deployed due to the limited frequency channels available.

II. BACKGROUND

A. CHAPTER OVERVIEW

This chapter discusses the IEEE 802.11 standard and its associated “family tree.” The security protocol used and its vulnerabilities are also discussed.

B. IEEE 802.11 INTRODUCTION

The first IEEE 802.11 standard [3] was established in 1997. This addressed the Medium Access Control (MAC) and physical (PHY) layers separately. Three different PHY layers were specified, namely Infrared (IR), Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). Both the FHSS and DSSS are in the Federal Communications Committee’s (FCC) 2.4 GHz Industrial, Scientific and Medical (ISM) band. The operations for all three PHY layers were specified at 1 and 2 Mbps. The IEEE 802.11b and 802.11a standards were subsequently released in 1999. Due to easier implementation of DSSS compared to Orthogonal Frequency Division Multiplexing (OFDM), IEEE 802.11b products hit the consumer market first. The higher bit rate of IEEE 802.11b gave wireless LANs worldwide recognition. Most recently, IEEE 802.11g products are emerging in the market. The relation of the four main IEEE 802.11 standards to the Open Systems Interconnection (OSI) layers is depicted in Figure 1. The 802 Logical Link Control (LLC) and 802.11 MAC are part of the OSI data-link layer. The 802.11, 802.11b, 802.11a and 802.11g differ in the OSI physical layer, where different frequency bands and modulations are used. [4].

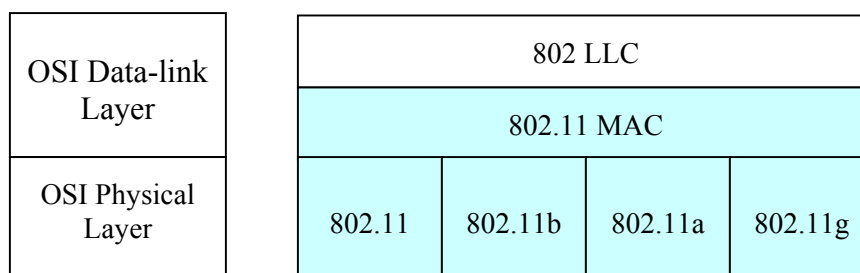


Figure 1. The OSI Layers and Corresponding IEEE 802.11 Standards (From Ref. 4.)

C. IEEE 802.11 STANDARDS

The following sections briefly describe the IEEE 802.11 standards that are discussed in this research – IEEE 802.11b, IEEE 802.11a, IEEE 802.11g and IEEE 802.11i. This information is obtained from the IEEE standard [3].

1. IEEE 802.11b

The IEEE 802.11b standard was released in 1999, specifying a higher bit rate of 11 Mbps and operation using DSSS in the 2.4 GHz ISM band. This is usually referred to as high-rate DSSS (HR/DSSS). It has the options of 5.5 Mbps and 11 Mbps, as well as 1 Mbps and 2 Mbps for backward compatibility with the legacy IEEE 802.11 standards. Three non-overlapping channels are allocated, providing a total available bandwidth of 83.5 MHz. The higher data-link rates are achieved using Quadrature Phase Shift Keying (QPSK) with either Complementary Code Keying (CCK) or Packet Binary Convolutional Coding (PBCC). The IEEE 802.11 working group adopted CCK due to its interoperability with the legacy IEEE 802.11 standards. Notwithstanding, PBCC is also defined as an option in IEEE 802.11b [5].

The block diagram for CCK modulations is shown in Figure 2. For 11-Mbps operation, the CCK uses 64 base spreading code words with good autocorrelation and cross-correlation properties. The input data is scrambled before passing to the data multiplexer. After the data multiplexer, six of the eight bits are used to choose one of the 64 complex codes. The chipping rate is maintained at 11 Mbps, while the symbol rate is decreased to 1.375 Mbps. Together with the remaining two bits from the data multiplexer, the Differential QPSK (DQPSK) modulator generates the required in-phase (I) and quadrature-phase (Q) data for modulation. For 5.5 Mbps, four complex codes are used instead of 64 [5].

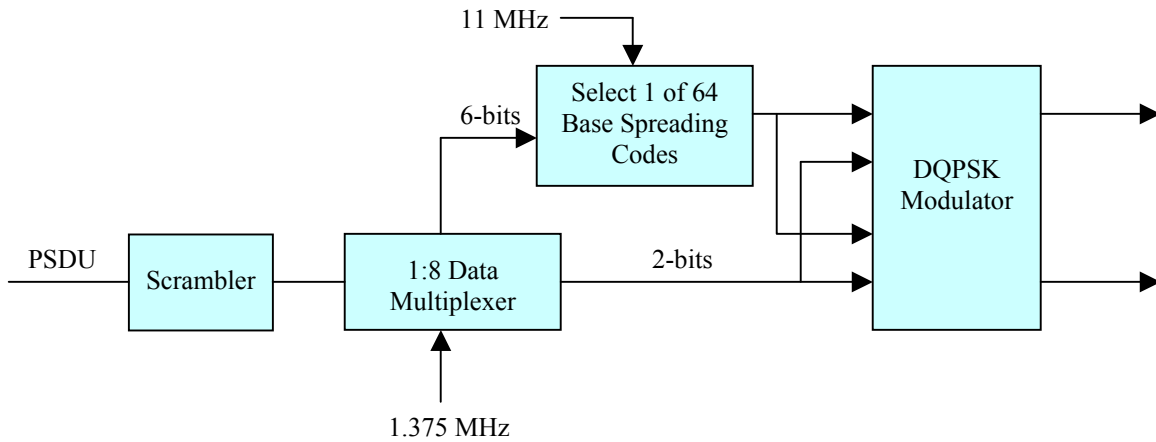


Figure 2. CCK Modulator (From Ref. 5.)

The block diagram for the PBCC modulation is shown in Figure 3. The PBCC uses a 64-state Binary Convolutional Code (BCC) with rate $R = 1/2$ and a cover sequence. The cover sequence is used to map the QPSK symbols and must be initialized with a 16-bit pattern (0011001110001011). The I and Q data are then pass into the modulator. Binary Phase Shift Keying (BPSK) is used for 5.5 Mbps, and QPSK is used for 11 Mbps [5].

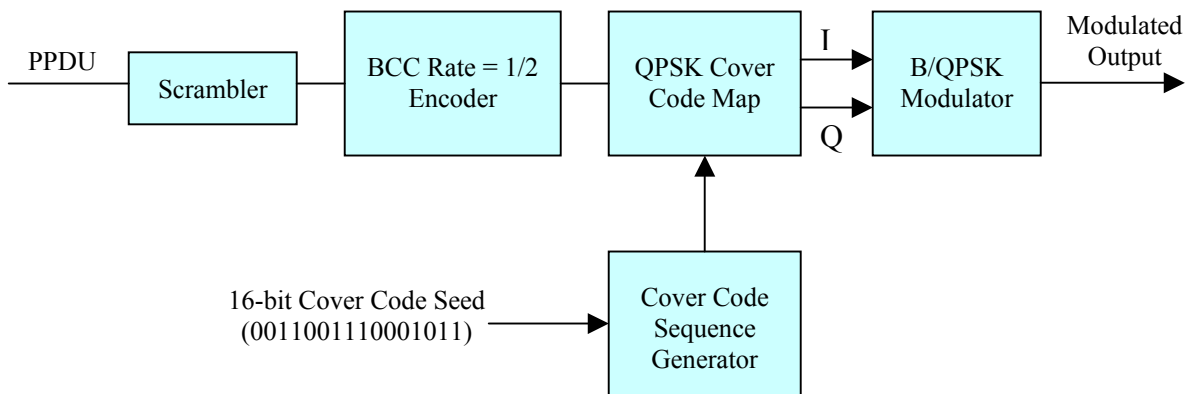


Figure 3. PBCC Modulator (From Ref. 5.)

2. IEEE 802.11a

The IEEE 802.11a operates in the 5-GHz Unlicensed National Information Infrastructure (U-NII) and has a data-link rate ranging from 6 to 54 Mbps. Orthogonal Frequency Division Multiplexing (OFDM) is the main feature in IEEE 802.11a that allows the high data-link rate of up to 54 Mbps [3]. The details are discussed in Chapter III.

3. IEEE 802.11g

The IEEE 802.11g can be thought of as a hybrid between IEEE 802.11a and IEEE 802.11b. Similar to IEEE 802.11b, it operates in the 2.4 GHz ISM band. For the data-link rate of 11 Mbps and below, it uses the same DSSS technology as IEEE 802.11b. At a data-link rate greater than 11 Mbps, up to 54 Mbps, it uses the OFDM technique similar to IEEE 802.11a. Due to this property of being backward compatible to IEEE 802.11b, it is ideal for organization transitioning from an 11 Mbps network to 54 Mbps. On the other hand, IEEE 802.11g uses the 2.4 GHz ISM band, which is congested and limited to three frequency channels. Despite having a longer range, it has less system capacity and would most likely experience more interference [5].

4. IEEE 802.11i Draft

The IEEE 802.11i is an addendum to the 802.11 standard that specifies new security protocols. The draft is almost complete and is unlikely to change significantly. Currently, the only available security protocol is Wired Equivalent Privacy (WEP), which is considered to be very vulnerable. The IEEE 802.1x with Extensible Authentication Protocol (EAP) and per-session key distribution forms a key part of the IEEE 802.11i [1]. This new type of secured wireless network is called a Robust Security Network (RSN). Currently, no RSN-capable products are available. As an interim solution to RSN, Wi-Fi has adopted the interim solution of Wi-Fi Protected Access (WPA), which makes use of Temporal Key Integrity Protocol (TKIP). The WEP and WPA are discussed in details in the following sections [6].

5. Summary of IEEE Standards

The following table summarizes the main 802.11 IEEE standard.

	802.11	802.11b	802.11a	802.11g
Standard Approved	July 1997	September 1999	September 1999	November 2002
Frequency	2.4 GHz	2.4 GHz	5 GHz	2.4 GHz
Available Bandwidth	83.5 MHz	83.5 MHz	300 MHz	83.5 MHz
Number of non-Overlapping Channels	3 (Indoor/Outdoor)	3 (Indoor/Outdoor)	4 (Indoor) 4 (Indoor/Outdoor) 4 (Indoor/Outdoor)	3 (Indoor/Outdoor)
Data-link Rates	1, 2 Mbps	5.5, 11 Mbps	6, 9, 12, 18, 24, 36, 48, 54 Mbps	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Modulation	FHSS, DSSS	DSSS	OFDM	DSSS, OFDM

Table 1. Summary of IEEE Standards (After Ref. 1.)

D. 802.11 SECURITY

The IEEE 802.11 wireless LAN is a double-edged sword. The wireless users gain mobility at the expense of greater security risk. In the beginning, the IEEE 802.11 task group defined only one protocol for security – Wired Equivalent Privacy (WEP). Most equipment on the market provides WEP only. More recently, the IEEE 802.11i task group has been defining a new type of wireless network called a Robust Security Network (RSN) to replace the WEP. However, it is still a draft and cannot be implemented yet. The security protocols currently available are WEP and WPA [6].

1. WEP

For most users, WEP is the only security protocol available. WEP is based on the Rivest Cipher 4 (RC4) algorithm, which is a symmetric stream cipher; i.e., both encryption and decryption share the same keys. Despite the security weaknesses associated with the WEP, it has the following advantages [6]:

- It is self-synchronizing for each message. This property is critical for a data-link-level encryption algorithm for which the “best effort” delivery is assumed.
- It is efficient and can be implemented in either hardware or software.
- The strength of its security relies on the difficulty of discovering the secret key through a brute-force attack.

The IEEE 802.11 standard specifies that WEP uses a 40-bit encryption key. Manufacturers made nonstandard extensions by using 104-bit keys, which are usually referred to as “128-bit” security. This discrepancy is due to the Initialization Vector (IV) of 24 bits. It is incorrect to state that “128-bit” security is used because the value of the IV is transmitted openly with the encrypted frames [6].

There are two parts to WEP security – the authentication and the encryption phase. As authentication is carried out openly, there is no way to verify if the subsequent messages are valid and is therefore pointless. This resulted in it being dropped from the Wi-Fi specification, despite being in the IEEE 802.11 standard. After association, encryption is based on RC4 algorithm [5].

2. RC4 and Initialization Vector (IV)

The Rivest Cipher 4 (RC4) algorithm is a symmetrical stream cipher. It takes in one byte of data and produces an output byte of encrypted data as shown in Figure 4. The encrypted stream of data is intended to resemble a sequence of random characters, regardless of the input data stream. Decryption is the reverse process and uses the same keys as for encryption. Hence, this is called a symmetric algorithm [6].

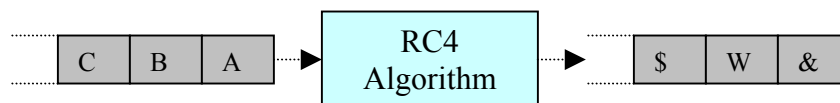


Figure 4. RC4 Stream Cipher (From Ref. 6.)

The main advantage of RC4 is that it is easily implemented and does not use complicated or time-consuming operations like multiplication. Every packet is initialized and encrypted separately. This ensures that any loss of packet will not affect the decryption of subsequent packets [6].

The Initialization Vector (IV) is used to prevent fixed-key encryption, which is vulnerable from a security viewpoint. The actual key used for the RC4 algorithm is a combination of a 24-bit IV and a 104-bit secret key as shown in Figure 5. For each packet, the IV changes, resulting in a different RC4 key being used for every packet. Although the IV is transmitted openly, theoretically it is very difficult to break the key unless the 104-bit secret key is known. This is based on the condition that the IV is never reused [6].

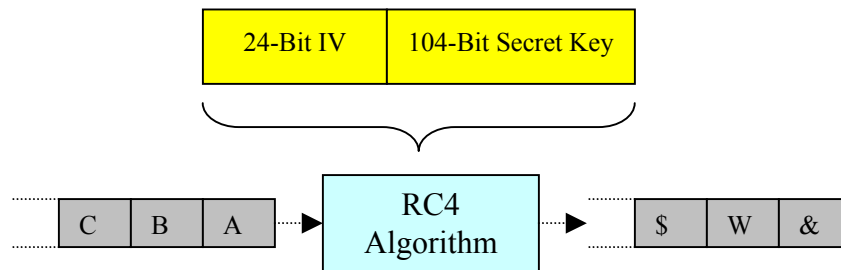


Figure 5. Combined RC4 Key Using IV (From Ref. 6.)

3. Weaknesses of WEP

The three weaknesses of RC4 as used in WEP are IV reuse, RC4 weak keys and direct key attack. Using a different IV for every packet is very secure. However, due to the limited size of the 24-bit IV, an IV collision is guaranteed after 2^{24} packets. As the IEEE 802.11 is capable of transmitting greater than 500 packets in a second, the IV space would be exhausted in approximately seven hours. In reality, a collision is likely to occur sooner because multiple clients are connected to the same AP. Once the key streams corresponding to their respective IV values are known, the packet can be decoded, regardless of whether the secret key is 40-bit or 128-bit in length [6].

RC4 works by creating a table, referred to as the “S-box” with the values 0 to 255. It then creates a second 256-byte table with the key, repeating until the table is full. The “S-box” is then rearranged based on values in the key table. Ideally, a bit change in the key would output a totally different key stream. Each bit should have a 50% chance of being different from the previous key stream. However, this was not the case. Some bits of the key have larger changes, while others have none. Coupled with the use of the changing IV, the probability of using weak keys is high. The use of weak keys can be overcome by discarding the first 256 bytes of the key stream. However, the first 256 bytes of the key stream cannot be discarded, as such a change would render the system inoperable with older systems [6].

The basic idea behind a direct-key attack is exploiting the weak key problems in the first few bytes. The plaintext of the first few bytes is usually an IEEE 802.1 LLC header. By watching these messages, a correlation can be made between the plaintext, ciphertext and secret key bytes, resulting in key extraction. Increasing the key size from 40 bits to 104 bits does not prevent an attack. It just increases the time taken to extract the key by a factor of 2.5 [6].

From the above, the conclusion that can be drawn about the WEP is that it is insecure and another security protocol is required for the IEEE 802.11. One of the interim protocols is the Wi-Fi Protected Access (WPA).

4. WPA

Due to the security vulnerability of WEP, Wi-Fi manufacturers decided to replace WEP with WPA. WPA is based in part on the draft 802.11i standard for RSN as it employs the Temporal Key Integrity Protocol (TKIP). The WPA is designed to run on existing hardware as a software upgrade. This provided a good transition to the eventual RSN for which existing Wi-Fi equipment can no longer be used.

To access WPA networks, all devices require a matching password. The password will initiate the encryption process based on TKIP. This is where WPA is substantially different from WEP. The TKIP takes the matching password as a starting point and derives its encryption keys mathematically from this. The TKIP regularly changes the en-

encryption keys so that the same encryption key is never used twice. This all happens automatically and is transparent to the user. These features make WPA more secure than WEP.

E. CHAPTER SUMMARY

Brief overviews of the IEEE 802.11 standards and their associated security protocols were presented. The vulnerability of the WEP and using the WPA as an interim solution prior to RSN were also discussed. The next chapter discusses the IEEE 802.11a standard, which includes key parameters of the standard, as well as the composition and functions of the MAC and PHY layer.

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III. IEEE 802.11A

A. CHAPTER OVERVIEW

This chapter provides an overview of the IEEE 802.11a standard, which includes key parameters of the standard, as well as the composition and functions of the MAC and PHY layer.

B. IEEE 802.11A OVERVIEW

Due to the rapid crowding of the 2.4 GHz ISM band and to achieve a higher data-link rate, the IEEE 802.11a standard was developed to operate in the 5 GHz U-NII band. The IEEE 802.11a standard employs Orthogonal Frequency Division Multiplexing (OFDM). Several subcarriers are sent in parallel using the Inverse Fast Fourier Transform (IFFT) and received using the Fast Fourier Transform (FFT) [7,8].

1. Specification

The IEEE 802.11a standard provides a variable data-link rate of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. The data-link rate of 6, 12 and 24 Mbps are mandatory in the standard. Tables 2 and 3 show the list of key parameters for the IEEE 802.11a standard [7].

A total of 52 OFDM subcarriers are used – 48 data subcarriers and 4 pilot tone subcarriers. The pilot tones are used at the receiver to estimate the residual phase error for the purpose of receiver synchronization. The IEEE 802.11a standard uses a variety of modulation techniques to achieve the data-link rate of 6 to 54 Mbps. The modulation techniques available are Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (QAM) and 64-QAM. Forward Error Correction (FEC), employing convolution coding is used with a coding rate of 1/2, 2/3 and 3/4 [7].

Data rate (Mbits/s)	Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

Table 2. Rate-dependent Parameters (From Ref. 7.)

Parameter	Value
N_{SD} : Number of data subcarriers	48
N_{SP} : Number of pilot subcarriers	4
N_{ST} : Number of subcarriers, total	52 ($N_{\text{SD}} + N_{\text{SP}}$)
Δ_F : Subcarrier frequency spacing	0.3125 MHz (=20 MHz/64)
T_{FFT} : IFFT/FFT period	3.2 μs ($1/\Delta_F$)
T_{PREAMBLE} : PLCP preamble duration	16 μs ($T_{\text{SHORT}} + T_{\text{LONG}}$)
T_{SIGNAL} : Duration of the SIGNAL BPSK-OFDM symbol	4.0 μs ($T_{\text{GI}} + T_{\text{FFT}}$)
T_{GI} : GI duration	0.8 μs ($T_{\text{FFT}}/4$)
T_{GI2} : Training symbol GI duration	1.6 μs ($T_{\text{FFT}}/2$)
T_{SYM} : Symbol interval	4 μs ($T_{\text{GI}} + T_{\text{FFT}}$)
T_{SHORT} : Short training sequence duration	8 μs ($10 \times T_{\text{FFT}}/4$)
T_{LONG} : Long training sequence duration	8 μs ($T_{\text{GI2}} + 2 \times T_{\text{FFT}}$)

Table 3. Timing-related Parameters (From Ref. 7.)

2. OFDM Physical Layer (PHY) Architecture

The main purpose of the OFDM PHY is to transmit Media Access Control (MAC) Protocol Data Units (MPDUs), under the direction of the 802.11 MAC layer. The OFDM PHY of the IEEE 802.11a standard is divided into the two following sublayers [7]:

- Physical Layer Convergence Protocol (PLCP)
- Physical Medium Dependent (PMD)

The MAC layer of the IEEE 802.11a standard exchanges information with the PLCP, using specific primitives through a PHY service access point. Under instruction of the MAC layer, the PLCP prepares the MPDUs for transmission. The PLCP also delivers incoming frames from the wireless medium to the MAC layer. The PLCP minimizes the dependence of the MAC layer on the PMD sublayer, by mapping MPDU into PLCP Protocol Data Unit (PPDU). The PPDU is a frame format suitable for transmission by the PMD. Figure 6 illustrates this process [7].

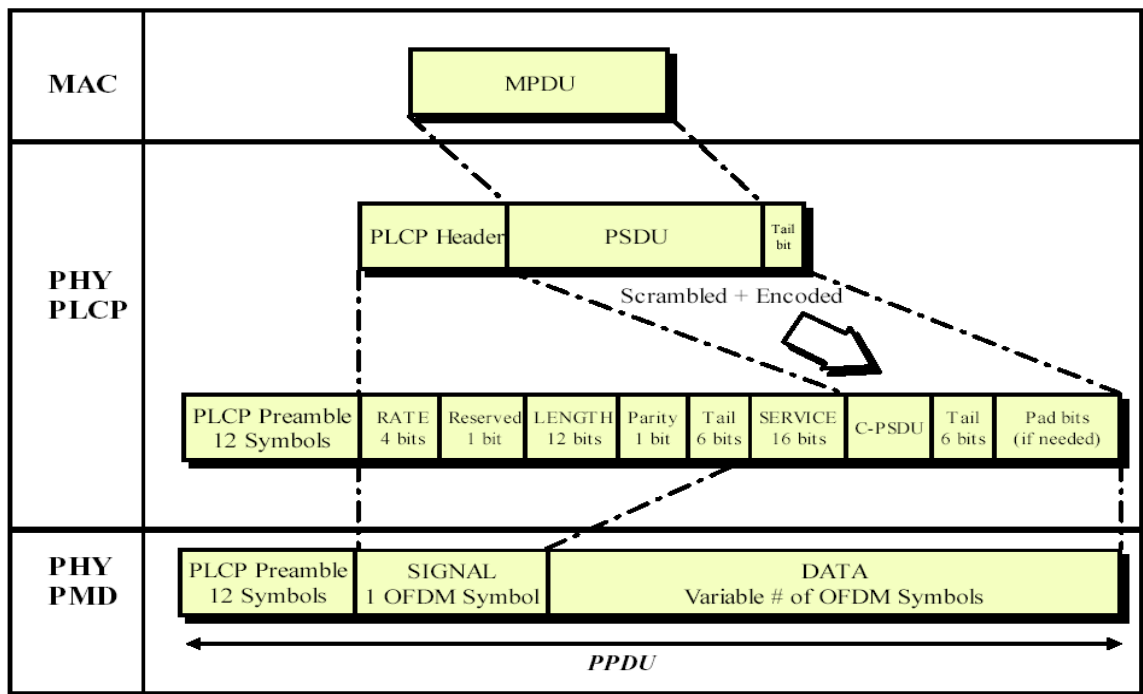


Figure 6. PPDU in IEEE 802.11a (After Ref. 7.)

The PPDU is unique to the OFDM PHY. It includes [7]:

- **PLCP Preamble.** This field is used to train and synchronize the demodulator for the purpose of acquiring incoming OFDM signal. The PLCP preamble is made up of ten short and two long symbols. The short symbols are used to train the receiver's Automatic Gain Control (AGC) and to provide a coarse estimate of the channel carrier frequency. The long symbols are used to fine-tune the channel carrier frequency [7].
- **SIGNAL.** There is a total of 24 bits in this field. This field contains information on the rate and length of the PHY Service Data Unit (PSDU). To ensure reliable reception, the SIGNAL is transmitted using the lowest rate. The first four bits (R1-R4) encode the rate and the fifth bit (R5) is a reserve bit. The following 12 bits (R6-R17) encode the length in bytes of the PSDU. The 18th bit is a parity check bit and the last six tail bits (R19-R24) flush the convolutional encoder and terminate the code trellis in the decoder [7].
- **DATA.** This field consists of 16 bits of service field, the encoded PSDU, six tail bits and optional padding bits. The data is transferred at a rate specified in the signal field [7].

The PLCP directs the PMD to transmit and receive the PHY entities between two stations through the wireless medium. To achieve this, the PMD needs to interface directly with the "air medium," as well as modulates or demodulates the transmission of each frame. The PLCP communicates with the PMD, using service primitives to determine the functions of transmission or reception [7].

3. MAC Layer

The IEEE 802.11a standard specifies the use of Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA). This is the same MAC technology as IEEE 802.11b. The CSMA-CA protocol avoids signal collision by requesting authorization for transmission for a specific amount of time prior to sending the information. The sender

broadcasts a request-to-send (RTS) frame, specifying the length of its signal. Upon receiving the clear-to-send (CTS) frame from the receiver, the sender transmits its information. Other devices in the area that also receive the CTS are aware that another sender is transmitting, and wait for the specified time duration to pass before contesting for information transfer [7].

C. CHAPTER SUMMARY

This chapter provided an overview of the IEEE 802.11a standard. This included key parameters of the standard, as well as the composition and functions of the MAC and PHY layer. The next chapter will provide an overview of the development of the prototype systems and all the tools used for data collection.

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IV. PROTOTYPE SYSTEMS

A. CHAPTER OVERVIEW

This chapter introduces the two prototype systems and their specifications – the Cisco Aironet 1400 wireless bridge and the Proxim Tsunami MP.11a wireless system. The supporting hardware and software used in this research are also discussed. These include the Xantrex Power Pack 400 Plus, the Socket GPS receiver with Bluetooth wireless technology, the “Microsoft Streets” software, and the File Transfer Protocol (FTP) software, “GuildFTPd FTP Daemon.”

B. CISCO AIRONET 1400 WIRELESS BRIDGE

The Cisco Aironet 1400 wireless bridge was designed to provide high-speed data-link rates in harsh outdoor environments, commonly on rooftops or radio towers. It operates in the 5.725 to 5.825 MHz U-NII band (four non-overlapping channels) with a variable data-link rate of 6 to 54 Mbps. Two bridges can be stacked to achieve a higher data-link rate. The wireless radio and antenna are housed in the same ruggedized housing, weighing five kilograms. The following sections describe the key specifications that are necessary for analyzing the performance and integrating the system onto military platforms [9].

1. Components

The Cisco Aironet 1400 wireless bridge is composed of three simple components – the bridge (consisting of the integrated wireless radio and antenna), the power injector, and the RF cables. Due to attenuation loss in the RF cables, Cisco’s specification limits the cable length to 100 m, when used with this power injector. Figures 7, 8 and 9 show the Cisco Aironet 1400 wireless bridge, power injector, and RF cables, respectively [9].



Figure 7. Cisco Aironet 1400 Wireless Bridge (From Ref. 9.)



Figure 8. Cisco Aironet 1400 Power Injector (From Ref. 9.)



Figure 9. Cisco Aironet 1400 RF Cables (From Ref. 9.)

2. Receiver Sensitivity

Table 4 shows the Cisco Aironet 1400 wireless bridge's required receiver sensitivity for the IEEE 802.11a radio at the respective data-link rate. Table 4 assumes a packet length of 3,200 bytes with a 10% Packet Error Rate (PER) [9].

Data-link Rate (Mbps)	Receiver Sensitivity (dBm)
6	- 83
9	- 83
12	- 83
18	- 82
24	- 79
36	- 76
48	- 72
54	- 70

Table 4. Cisco Aironet 1400 Wireless Bridge's Receiver Sensitivity versus Data-link Rate (From Ref. 9.)

3. Power Settings

Table 5 shows the seven available power settings for the Cisco Aironet 1400 wireless bridge, both in decibel (dBm) and milliwatts (mW) [8].

Power Setting (dBm)	Power (mW)
24	250
23	200
22	155
21	125
18	60
15	30
12	15

Table 5. Cisco Aironet 1400 Wireless Bridge's Transmit Power Settings (From Ref. 9.)

4. Key Integration Specifications

In order to integrate this prototype in military platforms, key specifications like dimension, weight, operating environments (temperature, altitude and vibration) and power consumption are necessary. Table 6 summarizes these key integration specifications [9].

Key Integration Parameters	Value
Dimension	29 cm x 29 cm x 11 cm
Weight	5 kg
Operational Temperature	-30° to $+55^{\circ}$
Operational Altitude	4206 m
Vibration	$0.001 \text{ G}^2/\text{Hz}$ from 5 – 100 Hz
Power	60 – 80 W

Table 6. Cisco Aironet 1400 Wireless Bridge's Key Integration Parameters (After Ref. 9.)

5. Received Signal Strength

The Cisco Aironet 1400 wireless bridge is equipped with a Received Signal Strength Indicator (RSSI). The RSSI displays a DC voltage that is proportional to the received signal strength, and is used for directional antenna alignment. Figure 10 shows the relationship between the received signal strength and the measured RSSI as given by data in [9].

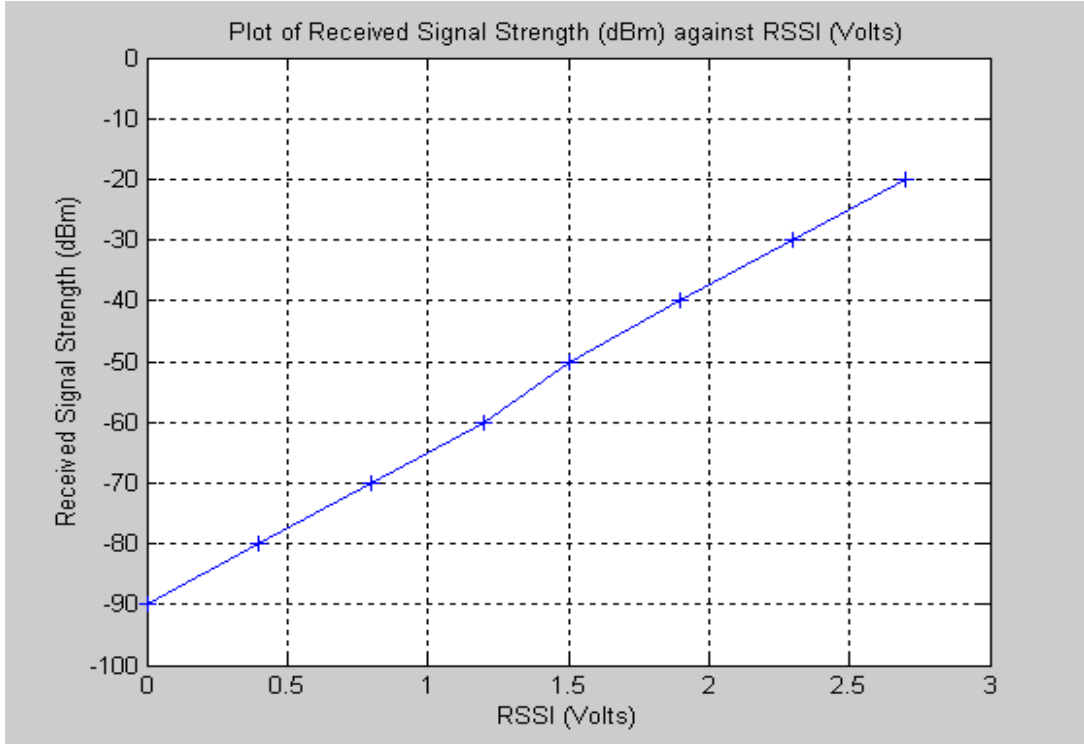


Figure 10. Cisco Aironet 1400 Wireless Bridge's Received Signal Strength versus Measured RSSI (After Ref. 9.)

C. PROXIM TSUNAMI MP.11A WIRELESS SYSTEM

The Proxim Tsunami MP.11a wireless system is robust and affordable and designed to provide high-speed data-link rates in an outdoor environment. It operates in three frequency bands: 5.25 to 5.35 GHz (four channels), 5.47 to 5.725 GHz (11 channels), and 5.725 to 5.850 GHz (four channels). It has a variable data-link rate of 6 to 54 Mbps, with an optimal performance achieved at 36 Mbps. When used in the United States, only eight frequencies are available: 5.28, 5.30, 5.32, 5.745, 5.765, 5.785, 5.805, and 5.825 GHz [10].

The Proxim Tsunami MP.11a wireless system consists of a Base Station Unit (BSU) and at least one Subscriber Unit (SU). The following sections describe the key specifications that are necessary for the performance analysis and integration onto military platforms [10].

1. Components

The Proxim Tsunami MP.11a wireless system is composed of two simple components, the Tsunami MP.11a wireless router and radio and a high-gain directional antenna (15 dBi). Figures 11 and 12 show these components, respectively [10].



Figure 11. Proxim Tsunami MP.11a Wireless Router and Radio (From Ref. 10.)



Figure 12. Proxim Tsunami MP.11a High-gain Directional Antenna (From Ref. 10.)

2. Receiver Sensitivity

Table 7 shows the Proxim Tsunami MP.11a wireless system's required receiver sensitivity for the respective radio's data-link rate. Table 7 assumes a packet length of 1,000 bytes with a 10% Packet Error Rate (PER) [10].

Data-link Rate (Mbps)	Receiver Sensitivity (dBm)
6	– 87
9	– 86
12	– 85
18	– 83
24	– 80
36	– 76
48	– 72
54	– 68

Table 7. Proxim Tsunami MP.11a Wireless System’s Receiver Sensitivity versus Data-link Rate (From Ref. 10.)

3. Power

The power output for the Proxim Tsunami MP.11a varies with the data-link rate. Table 8 shows the power output at each data-link rate for the respective frequency [10].

Frequency / Channels	Power Output (dBm) versus Data-link Rate (Mbps)			
	54	48	36	6-24
5.25 – 5.35 GHz (56 and 60)	14.5	15.5	17.4	17.4
5.25 – 5.35 GHz (64)	12.5	12.5	12.5	12.5
5.47 – 5.725 GHz (100, 104, 108, 112, 116, 120, 124, 128, 132, 136 and 140)	14.5	15.5	17.5	17.5
5.725 – 5.850 GHz (149, 153, 157 and 161)	13.5	15.5	17.5	18.5
5.725 – 5.850 GHz (165)	12.5	15.5	17.5	17.5

Table 8. Proxim Tsunami MP.11a Radio Output Power versus Data-link Rate (From Ref. 10.)

The transmitted power can be changed using the Graphical User Interface (GUI). The available power settings are “Max” (0 dB), “One Half” (– 3 dB), “One Quarter” (– 6

dB), “One Eighth” (–9 dB), and “Minimum” (–10 dB). Figure 13 shows the screen capture of the power setting [10].

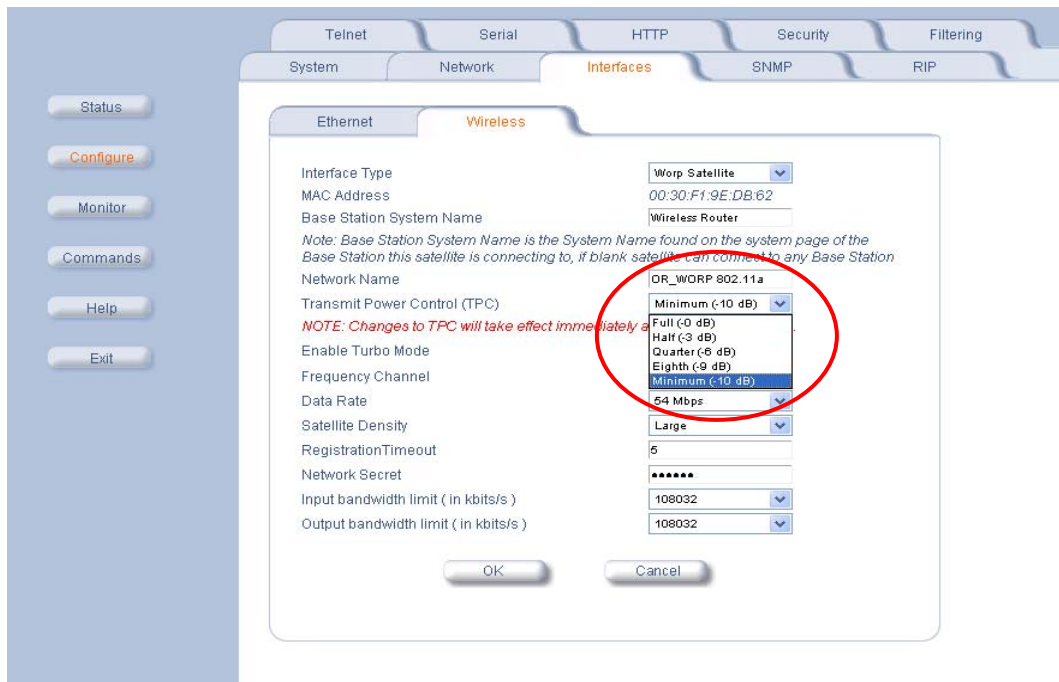


Figure 13. Screen Capture of Tsunami MP.11a Power Settings

4. Key Integration Specifications

Table 9 summarizes the key integration specifications for military platforms. These specifications include dimension, weight, operating temperature and power consumption [10].

Key Integration Parameters	Value
Radio Dimension	21.5 cm x 17.5 cm x 4 cm
Antenna Dimension	33.0 cm x 9.3 cm x 2.1 cm
Weight	1.08 kg
Operational Temperature	–20° to +75°
Power	10 – 30 W

Table 9. Proxim Tsunami MP.11a Wireless System’s Key Integration Parameters (After Ref. 10.)

The Proxim Tsunami MP.11a wireless system is lighter in weight and consumes less power. This makes it ideal for a soldier to transport it. However, due to its smaller EIRP and antenna gain, inferior performance is also expected.

5. Received Signal Strength

Just like the Cisco Aironet 1400 wireless bridge, the Proxim Tsunami MP.11a wireless system uses the Received Signal Strength Indicator (RSSI). However, the RSSI is implemented in the Graphical User Interface (GUI) for the Proxim Tsunami MP.11a wireless system. The “Link Test” is used to collect the RSSI value. Figure 14 shows the screen capture of this “Link Test.” To convert the RSSI to received signal strength, the RSSI value is subtracted by 92 (Received Signal Strength [dBm] = RSSI – 92) [10].

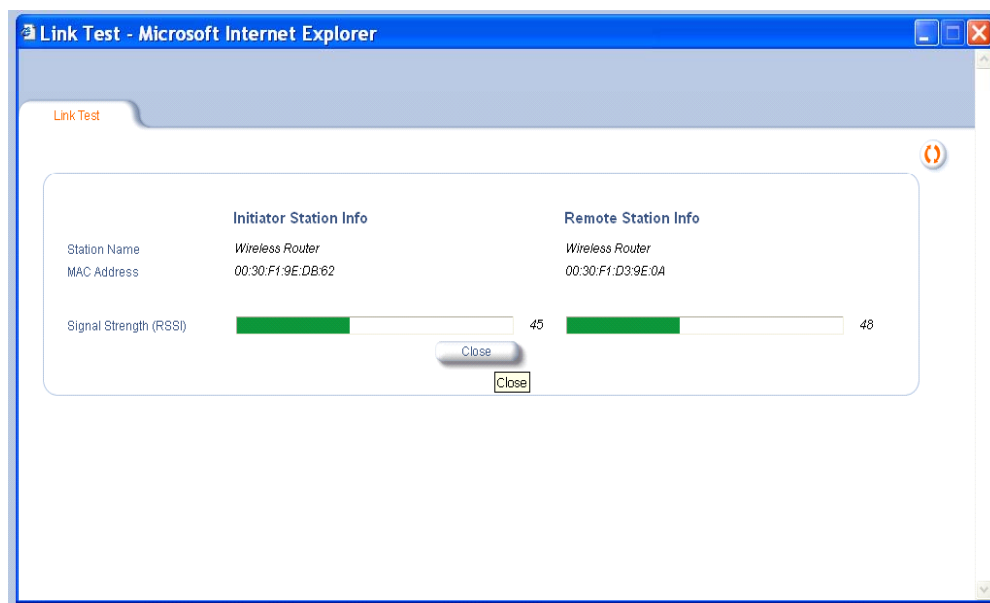


Figure 14. Screen Capture of Tsunami MP.11a “Link Test”

D. XANTREX POWER PACK 400 PLUS

This research was conducted at remote locations without an AC power supply. Therefore, there was a requirement for a portable battery pack. The Xantrex power pack has two AC output sockets of 115V (nominal), providing a maximum continuous power

output of 320 W. Based on a power consumption of 60 W, the Cisco Aironet 1400 wireless bridge can remain powered for two to three hours. In order to collect one set of data, two power packs were required. Figure 15 shows the Xantrex Power Pack 400 Plus [11].



Figure 15. Xantrex Power Pack 400 Plus (From Ref. 11.)

E. SOCKET GPS RECEIVER WITH BLUETOOTH WIRELESS TECHNOLOGY

In this research, there was a requirement to determine the distance separation between the root bridge and the non-root bridge. The Socket GPS receiver with Bluetooth wireless technology was used in this research. Together with the “Microsoft Streets” software (discussed in the next section), the distance separation calculation is automated. Moreover, with Bluetooth wireless technology, the GPS receiver need not be in the same location as the computer (within 10 m). Figure 16 shows the Socket GPS receiver [12].



Figure 16. Socket GPS Receiver (From Ref. 12.)

F. MICROSOFT STREETS

The Microsoft Streets software provides a detailed two-dimensional street map of the northern United States. It interfaces with the Socket GPS receiver via Bluetooth wireless technology to provide a coordinate location of the test points. Using the built-in features, the distance separation is automatically calculated. Figure 17 shows a screen capture of the Microsoft Streets software, where the distance separation between two test points is displayed.

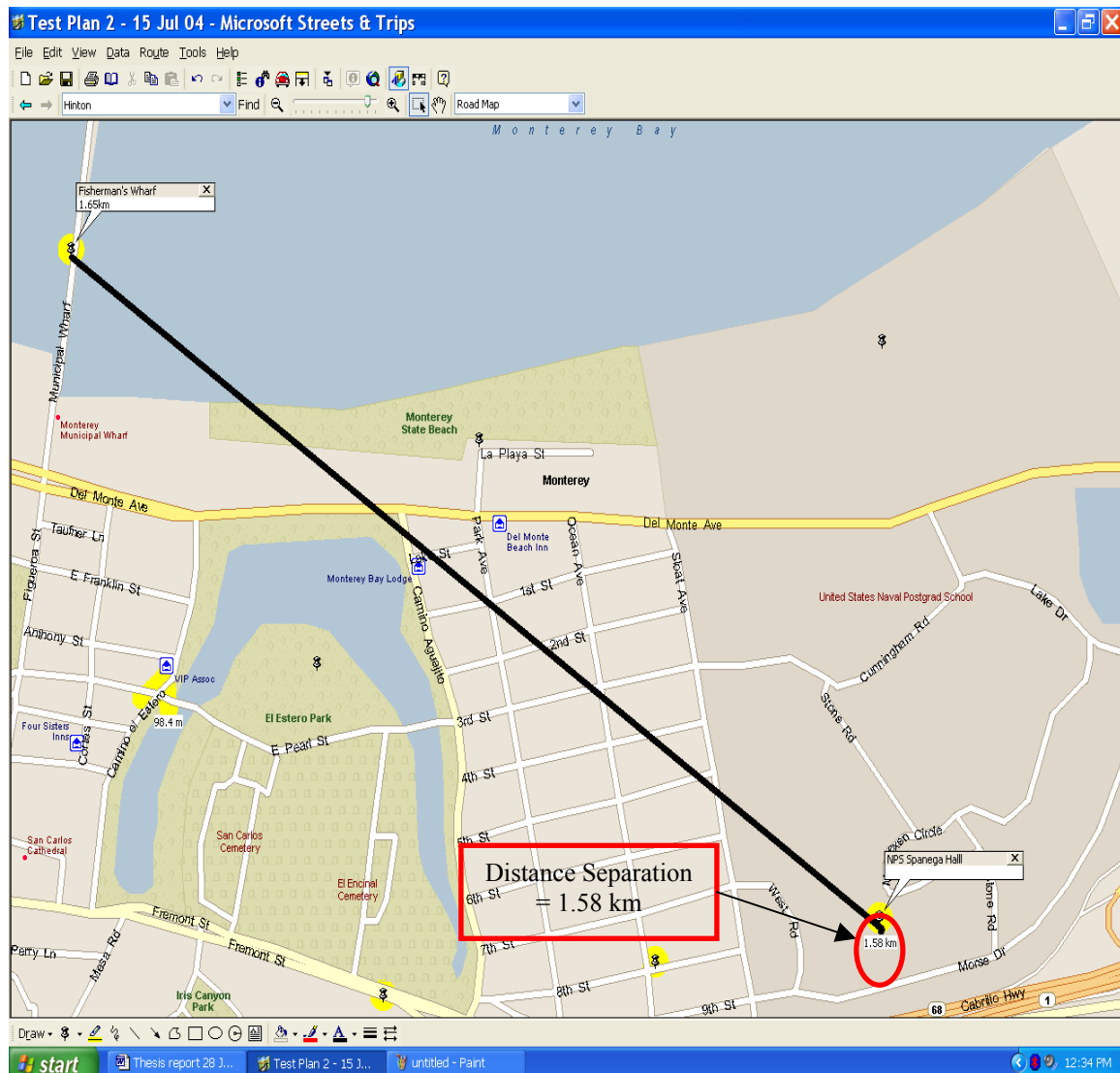


Figure 17. Screen Capture of Microsoft Streets Software

G. GUILDFTPD FTP SERVER SOFTWARE

The GuildFTPd FTP server software is free software downloaded from the Internet (Download.com). It is a File Transfer Protocol (FTP) server that allows the transfer of a large amount of data between the server and client. This free FTP server software was selected due to ease of use, and high recommendations from other users. This research uses this free FTP server software to determine the effective data throughput for the IEEE 802.11a wireless radio. Figure 18 shows a screen capture of this FTP server software, with data throughput displayed on the top portion of the screen capture.

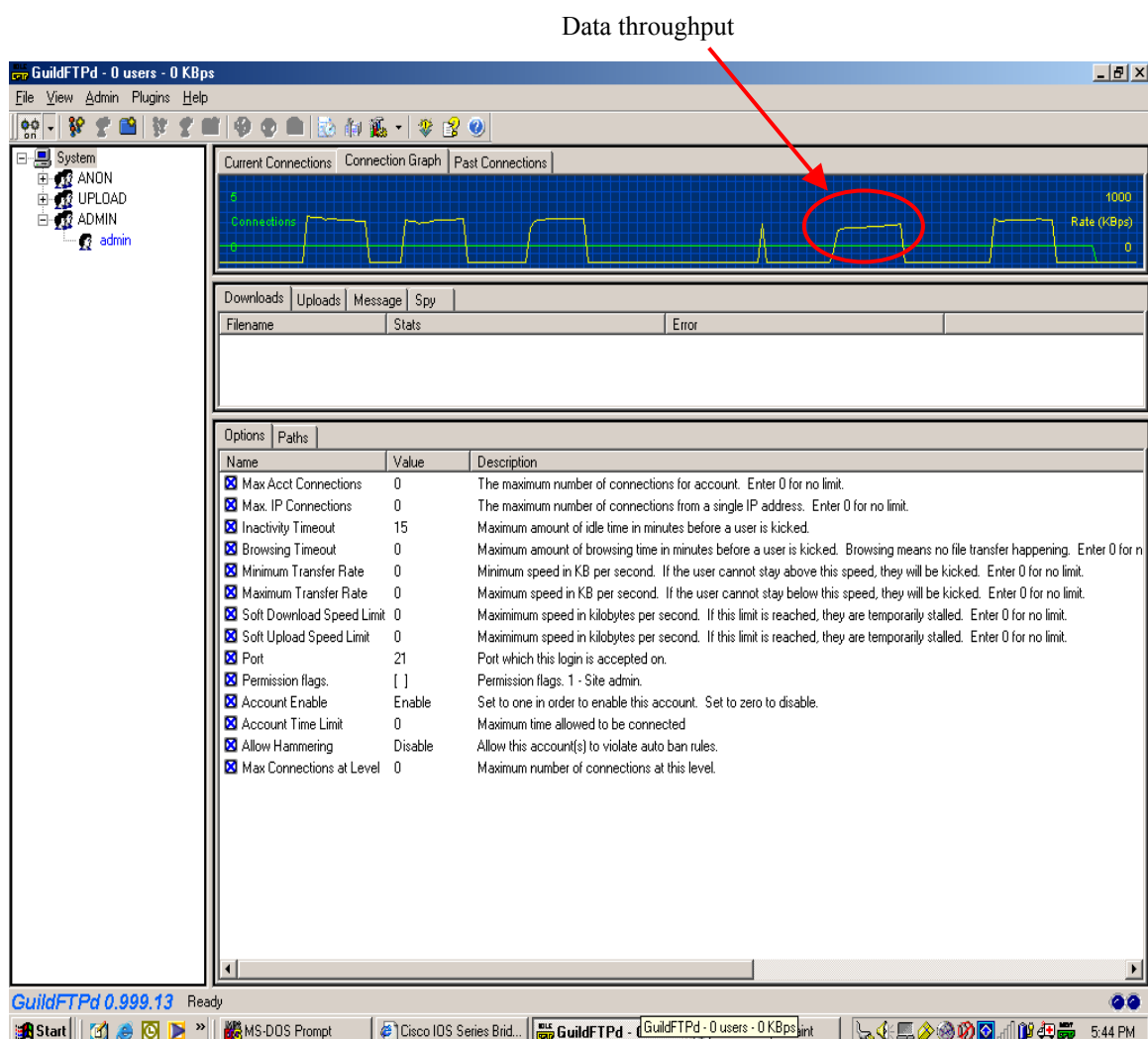


Figure 18. Screen Capture of GuildFTPd FTP Server Software

H. CHAPTER SUMMARY

This chapter introduced the reader to the Cisco Aironet 1400 wireless bridge and the Proxim Tsunami MP.11a wireless system, as well as their specifications. The supporting hardware and software used in this research were also presented.

The next chapter presents the field-testing results for the Cisco Aironet 1400 wireless bridge. This includes the laboratory setup and testing, the generation of the test plans, the field data collected, the observations made, and the conclusions drawn for all three operational environments.

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V. CISCO AIRONET 1400 WIRELESS BRIDGE'S TESTING, RESULTS AND DISCUSSIONS

A. CHAPTER OVERVIEW

This chapter presents the laboratory setup and testing, the generation of the test plans, and the collection of data from field-testing. From the data collected, a performance analysis was performed to study the signal attenuation, the Packet Error Rate (PER), and the effective data throughput under all three operational environments: land, water, and vegetation.

B. LABORATORY SETUP AND TESTING

The Cisco Aironet 1400 wireless bridge was set up under laboratory conditions to ensure the proper integration and functionality between the supporting hardware and software with the wireless bridge prior to field-testing.

Figure 19 shows the laboratory setup of the Cisco Aironet 1400 wireless bridge. The equipment on the left of the figure represents the root bridge, which is more commonly known as the AP or master. The equipment on the right represents the remote end or non-root bridge. Both root and non-root bridge are made up of a wireless bridge, a power injector, a notebook, a Xantrex Power Pack, a set of RF cables, an Ethernet cable, and two power cables. The root and non-root bridges were placed six meters apart, with the power set to the lowest of 12 dBm. The IP addresses of the bridges and notebooks were then configured.

The entire range of data-link rate from 6 to 54 Mbps was tested. Figure 20 shows the screen capture of the setting of data-link rate. A particular data-link rate was set by selecting the "Require", with the rest set to "Disable." To prevent any further compression, files containing pictures were used and zipped. Two file sizes of approximately 40 Mbytes and 160 Mbytes were used to observe the effect of the file size on the data throughput. It was concluded that both file sizes showed approximately the same data throughput. Hence the file size of 40 Mbytes was selected for field-testing.

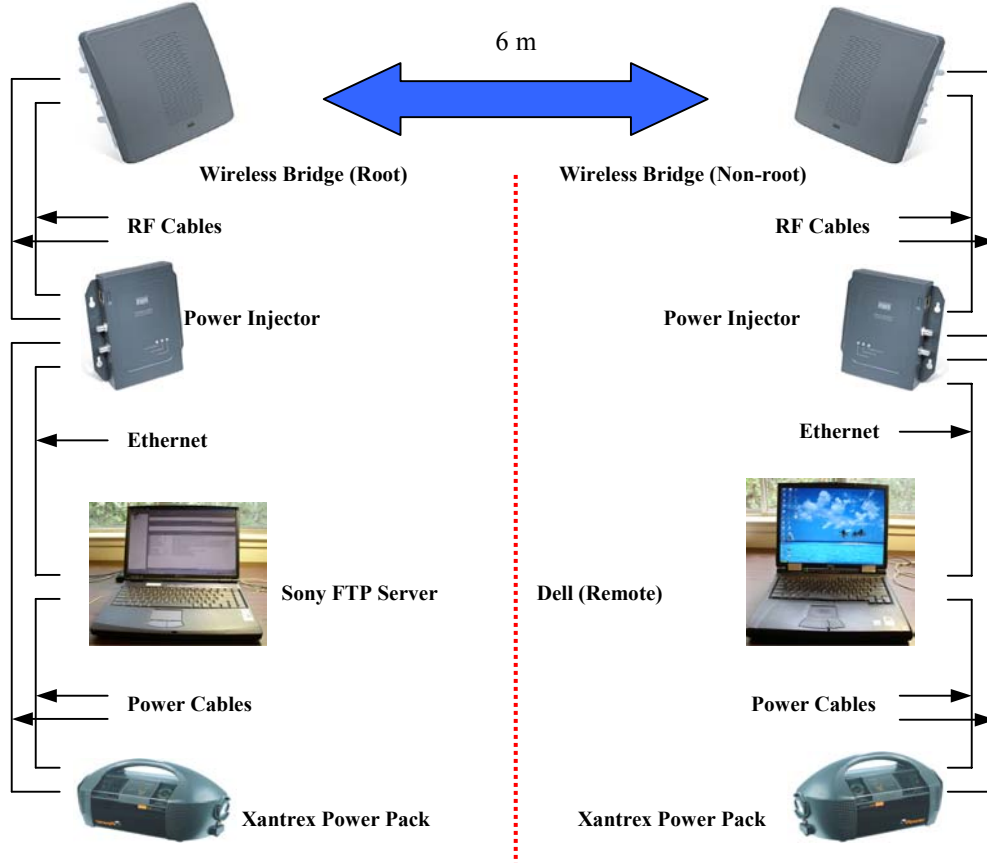


Figure 19. Cisco Aironet 1400 Wireless Bridge Laboratory Setup

During initial laboratory testing, the root bridge was set up using a Pentium-I computer with 40 Mbytes of RAM. The data throughput for a higher data-link rate was very low. Subsequently, the computer was changed to a Pentium-III with 256 Mbytes of RAM. Further testing showed a maximum data throughput of approximately 20 Mbps at the data-link rate of 54 Mbps. During both setups, a Pentium-IV notebook with 640 Mbytes of RAM was used in the non-root bridge.

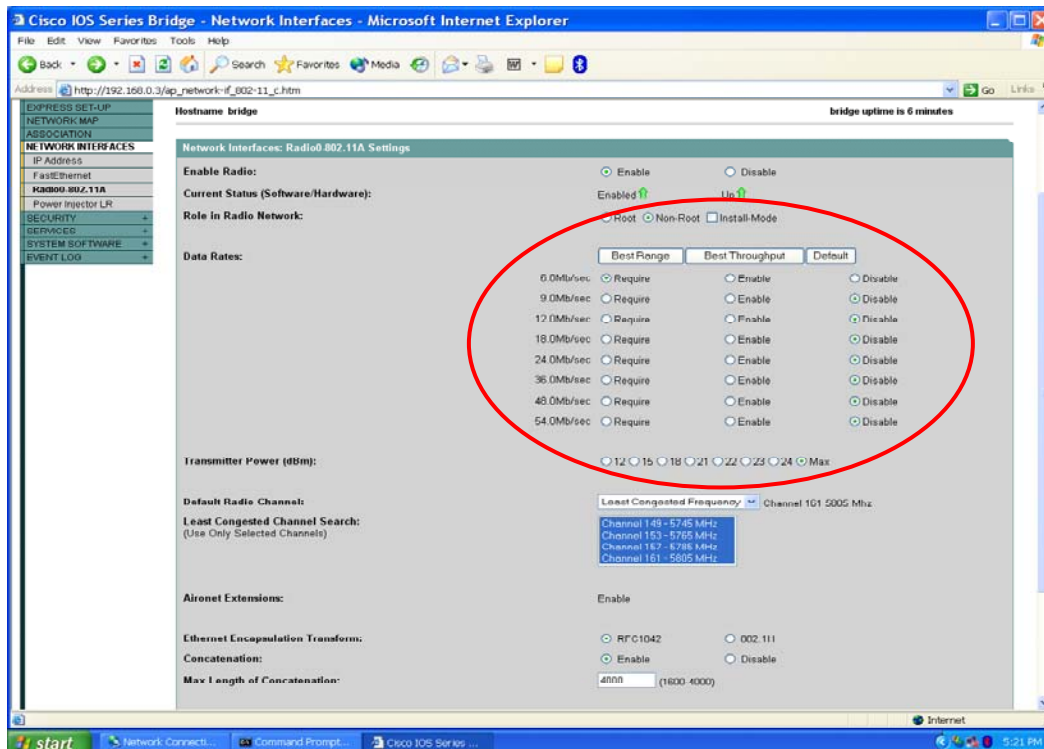


Figure 20. Screen Capture of the Setting of the Data-link Rate (Cisco)

C. LAND ENVIRONMENT TESTING

1. Test Plan

Using Microsoft Streets, the initial test plan was generated based on a map study of the area around NPS with a direct LOS. A search radius of three kilometers was chosen, based on the assessment that a direct LOS could not be achieved for a distance greater than three kilometers (map study) and due to the logistic constraints of working alone. The remote-end antenna height was also fixed at approximately two meters. This is similar to an operational condition, in which the need to raise an antenna is eliminated to prevent the spotting of the antenna. Ten preliminary test points were selected.

As Microsoft Streets' altitude data was assessed to be inaccurate, an on-the-ground check had to be conducted to determine if any signal was received at the ten selected preliminary test points. The root Cisco Aironet 1400 wireless bridge was set up on the roof of Spanagel Hall and the remote end was set up sequentially at the ten prelimi-

nary test points. During the preliminary checks, a data-link rate of 6 Mbps was set due to its robustness. Figure 21 shows all the ten test points: the junction of Eighth Street and Ocean Avenue, the Monterey Peninsula College (MPC), the El Estero Park, the wharf, the junction of Watson Street and Franklin Street, the Defense Language Institute (DLI), the Del Monte Beach, the Hilby pond, the Best Western at the Beach, and the Bay Street along the coast of Monterey Bay.

On-the-ground checks revealed that only test points one to six had a direct LOS and managed to register some signal strength. Test points seven, nine, and ten did not have LOS due to the small knoll leading to Del Monte Beach. Test point eight was slightly out of sight and also received no signal. An additional test point at NPS's baseball field (0.8 km) was also checked. With slight foliage blockage, a large fluctuation of signal strength was observed. An attempt to carry out a file transfer was impossible due to the unstable nature of the link.

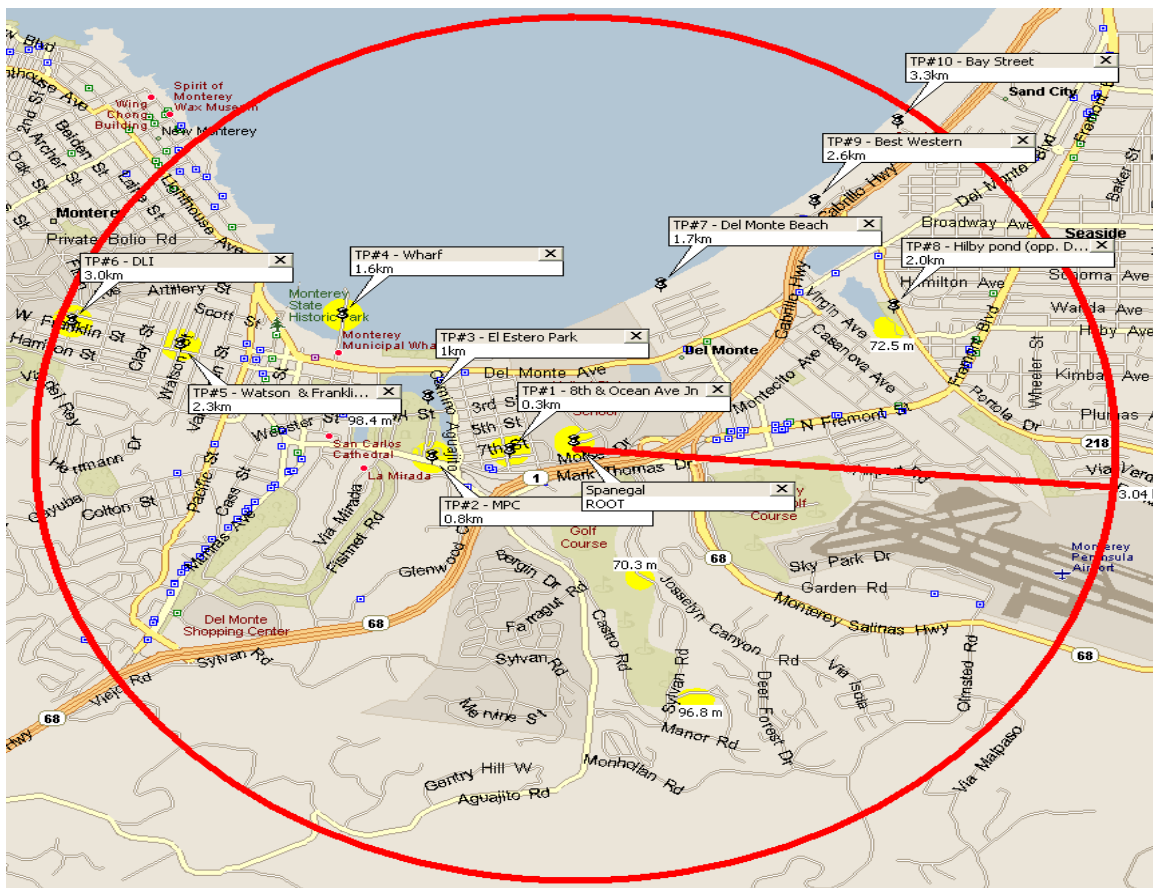


Figure 21. Preliminary Test Points (Land)

From the preliminary check, it was concluded that a direct LOS was critical and essential for IEEE 802.11a networks. After these preliminary checks, it was determined that only test points one to six would be used for actual field data collection. Finally, with the remote antenna's height set at two meters, the range performance of the wireless bridge was expected to be less than the stated specifications in the data sheet.

2. Overall Performance Data

Test points one to six were used for field data collections, with a maximum range of three kilometers. The performance data for the Cisco Aironet 1400 wireless bridge in a land environment is summarized in Table 10. The distance separation was determined using GPS and Microsoft Streets. The received signal strength in dBm was converted from the Received Signal Strength Indicator (RSSI) voltage recorded (see Figure 10). The maximum data-link rate, the maximum data throughput, and the average Packet Error Rate (PER) were measured and recorded from the FTP server software and the Cisco Aironet 1400 wireless bridge Graphical User Interface (GUI).

Test Point	Range (m)	Received Signal Strength (dBm)	Maximum Data-link Rate (Mbps)	Maximum Data Throughput (Mbps)	Average PER (%)
1	300	-23	54	20.33	3.51
2	700	-26	54	20.80	3.37
3	1,000	-38	54	19.98	5.57
4	1,600	-48	54	19.64	5.92
5	2,350	-53	54	19.23	7.49
6	3,000	-58	54	19.05	7.60

Table 10. Overall Measured Performance Data in a Land Environment (Cisco)

3. Received Signal Strength

The measured received signal strength versus range at the respective test points is plotted in Figure 22 (The straight-line segments just join the data points.). The measured received signal strength decreased with increasing range.

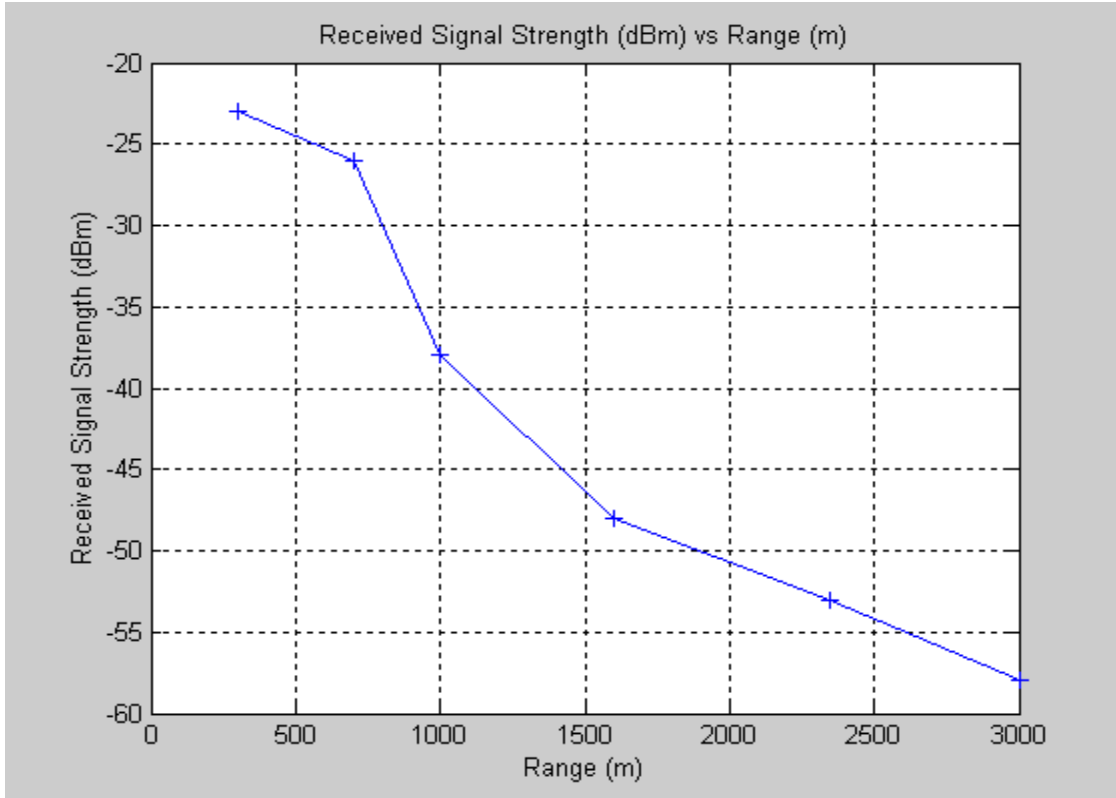


Figure 22. Measured Signal Strength at Receiver versus Range (Cisco – Land)

From the graph in Figure 22, it was observed that the first two test points achieved better-measured received signal strength. The reasons for these observations were assessed to be the proximity of both test points to the root wireless bridge.

4. Maximum Data-link Rate

From Table 10, the data-link rate of 54 Mbps was achieved up to the range of three kilometers in a land environment.

5. Maximum Data Throughput and Packet Error Rate

Figures 23 and 24 show the maximum measured data throughput and measured average packet error rate versus range at all six test points. From these graphs, it was observed that the packet error rate increased with increasing range. This in turn led to lower data throughput. It was also observed that test point two had lower packet error rate and higher data throughput than test point one. One possible reason for this observation was the multipath effect. Based on the better-than-expected received signal strength, it was assessed that test point two was adding multipath signals constructively, leading to better performance.

It was concluded that the average measured data throughput for the data-link rate of 54 Mbps at distances up to three kilometers was approximately 20 Mbps and the average measured packet error rate was approximately 5.5%.

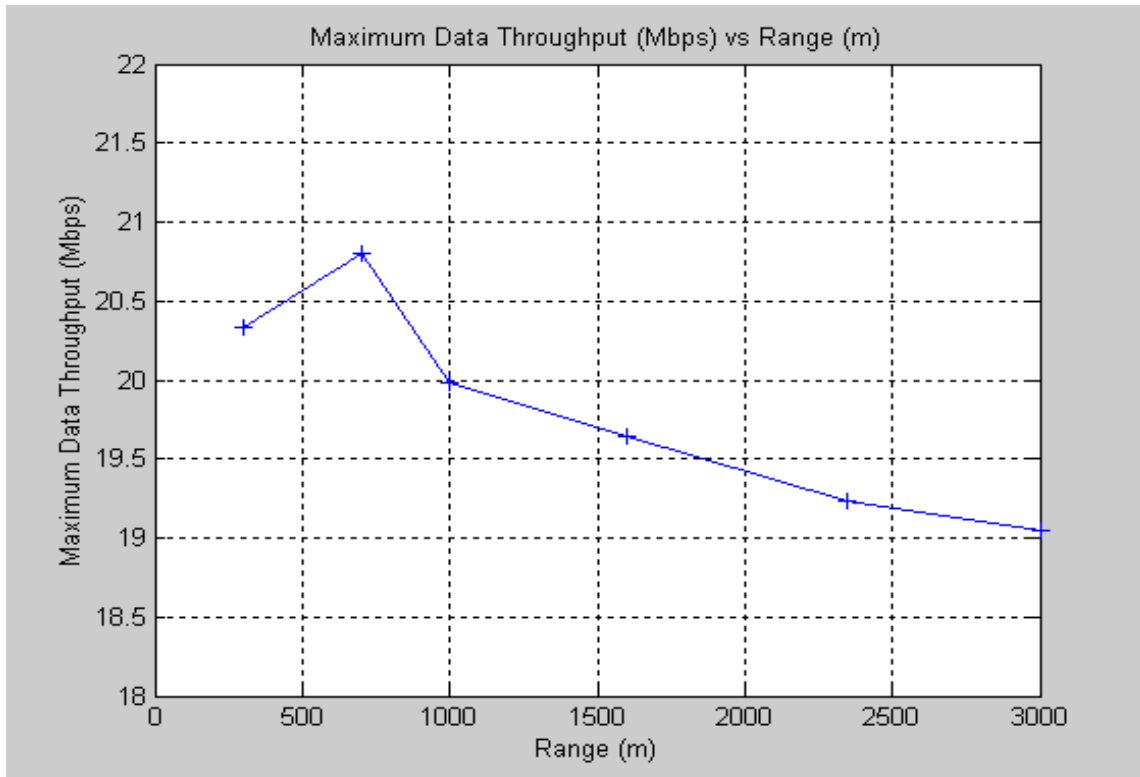


Figure 23. Maximum Measured Data Throughput versus Range (Cisco – Land)

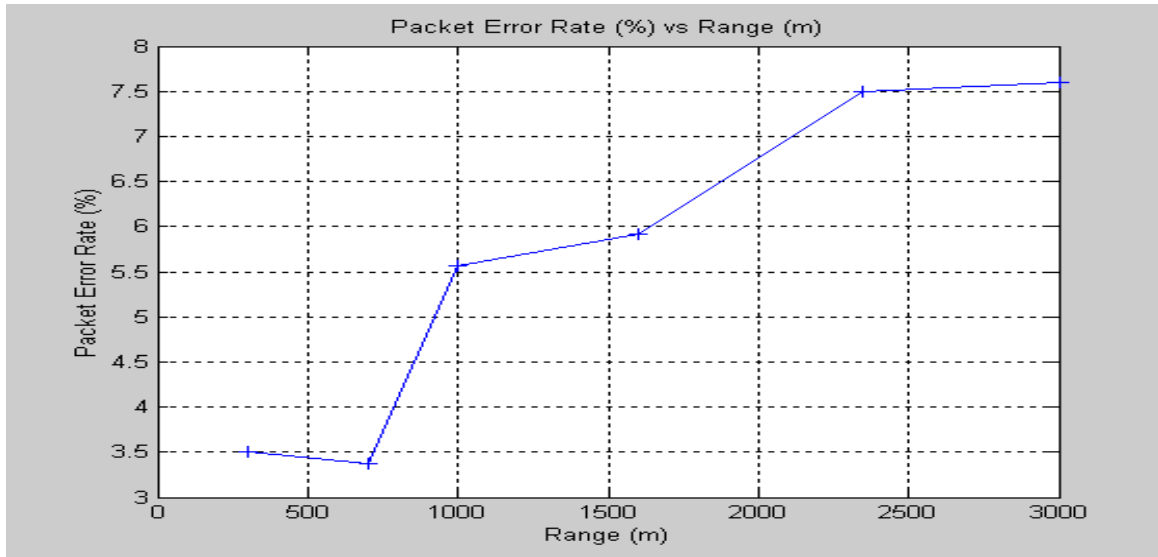


Figure 24. Measured Average Packet Error Rate versus Range (Cisco – Land)

6. Data Throughput versus Data-link Rate

Table 11 consolidates the measured performance data collected on data throughput achieved over the entire range of data-link rate (6 to 54 Mbps). These performance data were collected for all six test points.

Test Point	Range (m)	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
		6	9	12	18	24	36	48	54
1	300	2.76	5.03	5.85	8.50	10.69	14.84	18.85	20.33
2	700	2.73	4.84	5.83	8.18	10.15	14.23	17.78	20.80
3	1,000	2.69	4.75	5.58	8.13	10.07	14.12	18.01	19.98
4	1,600	2.66	4.69	5.42	8.00	10.03	14.15	17.70	19.64
5	2,350	2.69	4.66	5.38	8.19	10.39	14.17	18.31	19.23
6	3,000	2.63	4.70	5.28	8.15	10.27	14.08	17.60	19.05
Average Data Throughput		2.69	4.78	5.56	8.19	10.27	14.27	18.04	19.84

Table 11. Measured Data Throughput versus Data-link Rates at Various Ranges (Cisco – Land)

Figure 25 plots the measured data throughput achieved over the entire range of data-link rate (6 to 54 Mbps). Test Points one to six are plotted in red, blue, magenta, green, black and light blue, respectively. From the graph, it was observed that the data throughput at any given data rate degraded as distance increased. However, this degradation was insignificant. The average measured data throughputs achieved for 6, 9, 12, 18, 24, 36, 48 and 54 Mbps were 2.69, 4.78, 5.56, 8.19, 10.27, 14.27, 18.04 and 19.84 Mbps, respectively. It was also concluded that as the data-link rate increased, the data throughput deviated further from theoretical values.

At lower data-link rates, the data throughput achieved for all six test points were very close to one other. At a higher data-link rate (especially 54 Mbps), the deviation between the data throughput recorded at different test points was greater. One possible reason for this is that, at 54 Mbps, the modulation technique used is 64-QAM, which is more prone to noise or interference. Therefore, at a larger range the effect is more severe.

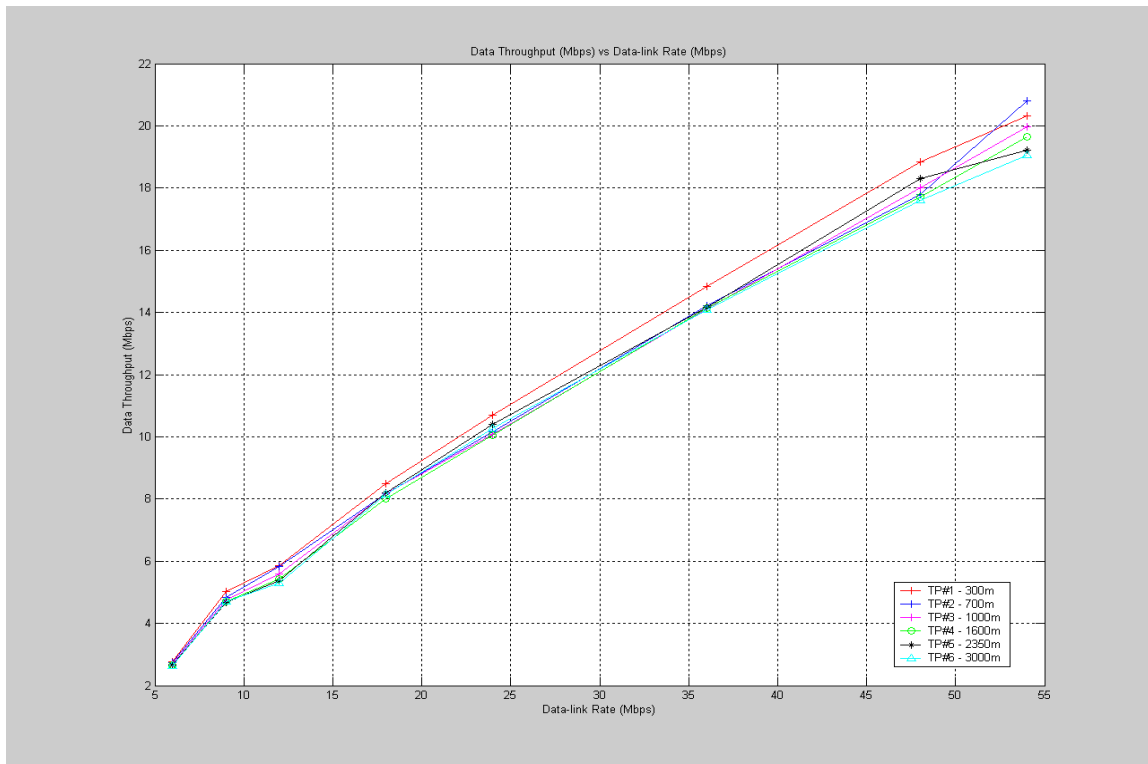


Figure 25. Plot of the Measured Data Throughput versus Data-link Rates at Various Ranges (Cisco – Land)

7. Effect of WEP on Performance

The effect of using WEP on data throughput was recorded as part of the field-testing. Test Point one was used for this test because it had the best-received signal strength. Table 12 shows the measured data throughput achieved when WEP (40-bit and 128-bit) was used at various data-link rates. Figure 26 shows the plot, where no WEP, 40-bit WEP and 128-bit WEP are plotted in red, blue and green, respectively.

WEP	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
	6	9	12	18	24	36	48	54
No	2.76	5.03	5.85	8.50	10.69	14.84	18.85	20.33
40-Bit	2.78	5.05	5.85	8.56	10.85	15.50	19.00	20.60
128-Bit	2.78	5.05	5.90	8.60	10.91	15.80	19.05	20.77

Table 12. Effect of WEP on Measured Data Throughput (Cisco – Land)

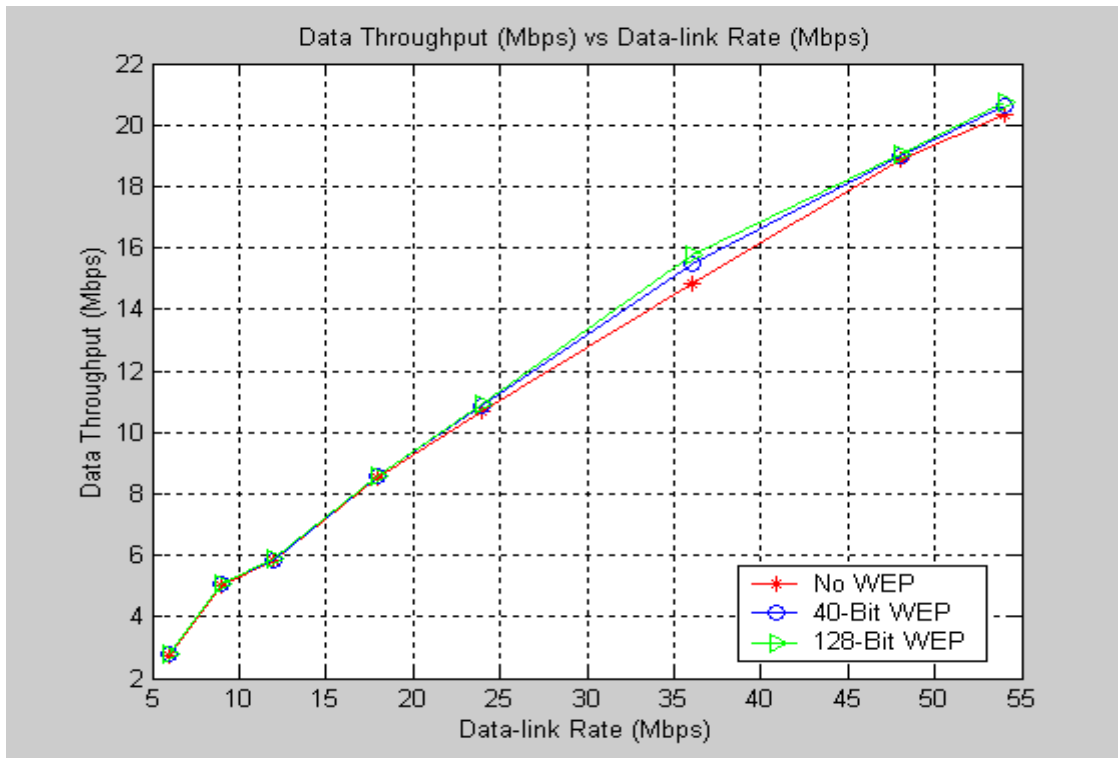


Figure 26. Plot of the Effect of WEP on Measured Data Throughput (Cisco – Land)

From Figure 26, it was observed that, at a data-link rate of 18 Mbps and below, the data throughput recorded for using WEP (40-bit and 128-bit) was very similar to that recorded without the use of WEP. As the data-link rate increased above 18 Mbps, the use of WEP improved data throughput slightly. It was also observed that 128-bit WEP performed marginally better than 40-bit WEP. The WEP, using RC4, is a symmetrical stream cipher. One byte of data input will generate one byte of encrypted data output. Hence the data throughput was not degraded.

Table 13 shows the packet error rate recorded when WEP (40-bit and 128-bit) was used at various data-link rates. Figure 27 shows the plot, where no WEP, 40-bit WEP and 128-bit WEP are plotted in red, blue and green, respectively.

WEP	Packet Error Rate (%) at Varying Data-link Rates (Mbps)							
	6	9	12	18	24	36	48	54
No	3.59	3.61	3.60	3.49	3.68	3.06	2.45	2.20
40-Bit	3.56	3.60	3.60	3.49	3.55	2.80	2.30	1.98
128-Bit	3.56	3.60	3.60	3.50	3.45	2.45	2.25	1.77

Table 13. Effect of WEP on Measured Packet Error Rate (Cisco – Land)

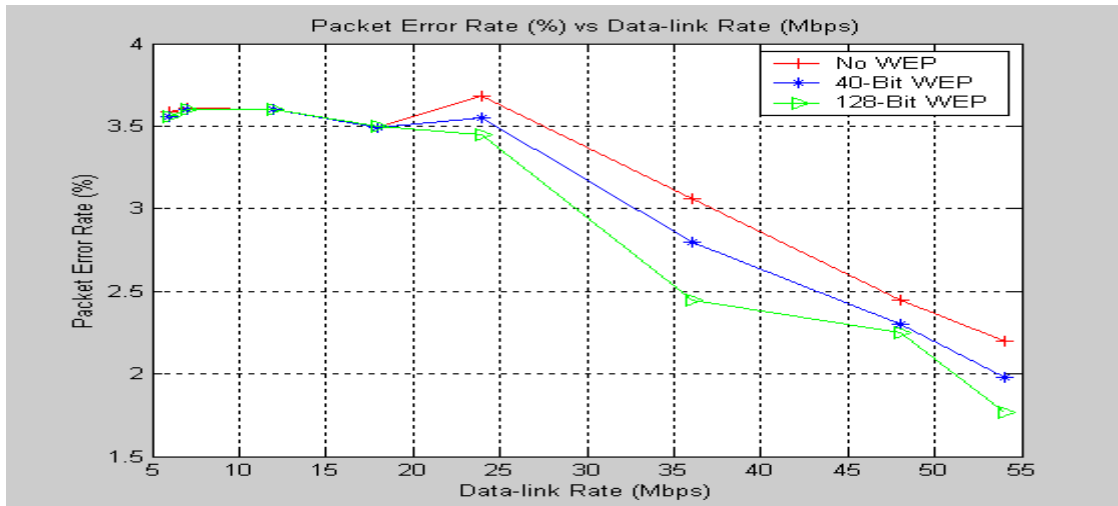


Figure 27. Plot of the Effect of WEP on Measured Packet Error Rate (Land)

From Figure 27, it was observed that, for a data-link rate of 18 Mbps and below, the packet error rate was almost identical. This was regardless of whether WEP was used or not. However, as the data-link rate increased above 18 Mbps, using WEP decreased the packet error rate slightly. The 128-bit WEP was also observed to perform marginally better than the 40-bit WEP. This observation was consistent with the observation made in Figure 26, where better data throughput was observed above 18 Mbps.

Contrary to theory, the field data recorded showed that the use of WEP with QAM (24 to 54 Mbps) improved the performance marginally. Despite this observation, the only conclusion that could be drawn from this test was that using WEP did not degrade the performance of the IEEE 802.11a network. As the improvement in performance was so marginal and coupled with the limited field data collected, the observation made was most likely due to ever-changing environmental conditions.

8. Effect of Packet Length Variation on Performance

At test point one, where the best-received signal strength was recorded, the effect of the varying packet length on the data throughput and the packet error rate was examined. Tables 14 and 15 consolidate the field data collected for the data throughput and the packet error rate. Figures 28 and 29 show the plots, where the red line represents a packet length of 4,000 bytes and the blue line represents a packet length of 1,600 bytes.

Packet Length (bytes)	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
	6	9	12	18	24	36	48	54
1600	2.76	5.03	5.85	8.50	10.69	14.84	18.85	20.33
4000	2.55	4.80	5.50	8.20	10.32	14.66	18.68	19.80

Table 14. Effect of Packet Length on Measured Data Throughput
(Cisco – Land)

Packet Length (bytes)	Packet Error Rate (%) at Varying Data-link Rates (Mbps)							
	6	9	12	18	24	36	48	54
1600	3.59	3.61	3.60	3.49	3.68	3.06	2.45	2.20
4000	7.63	7.62	7.67	7.64	7.78	7.62	7.05	7.05

Table 15. Effect of Packet Length on Measured Packet Error Rate
(Cisco – Land)

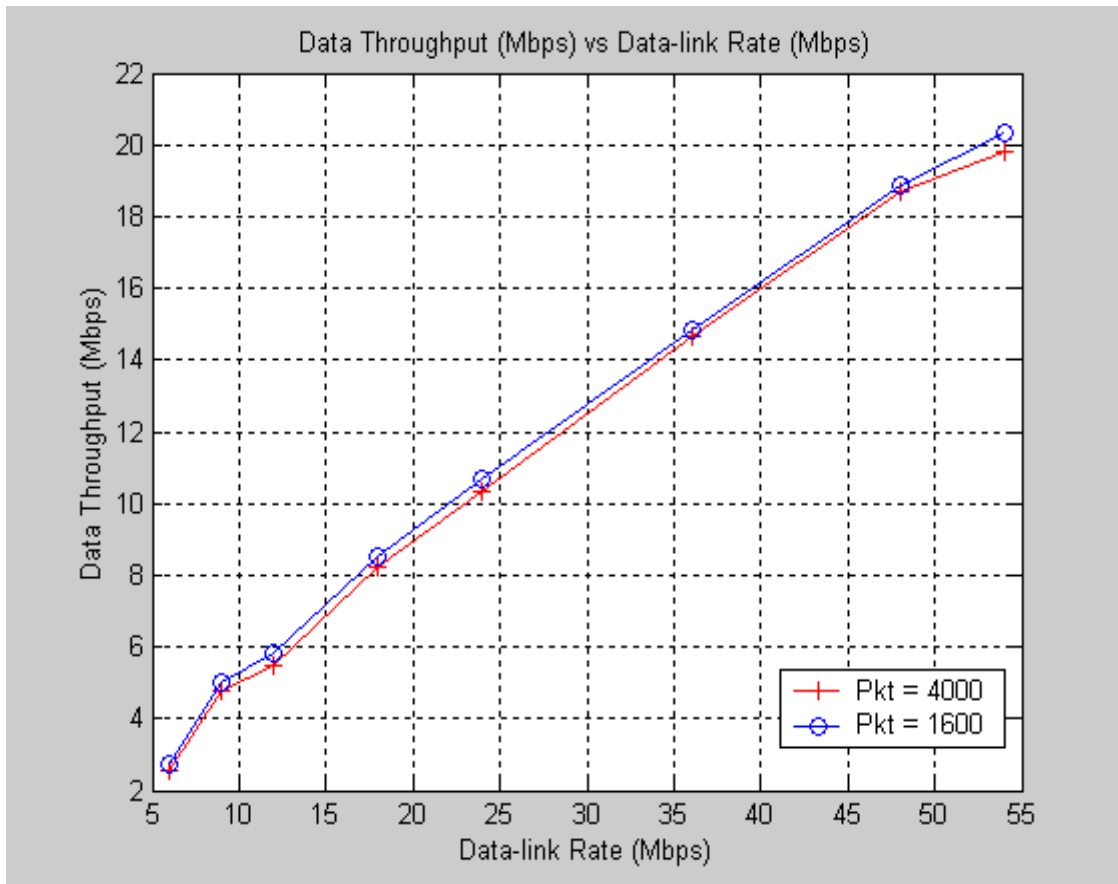


Figure 28. Plot of the Effect of Packet Length on Measured Data Throughput
(Cisco – Land)

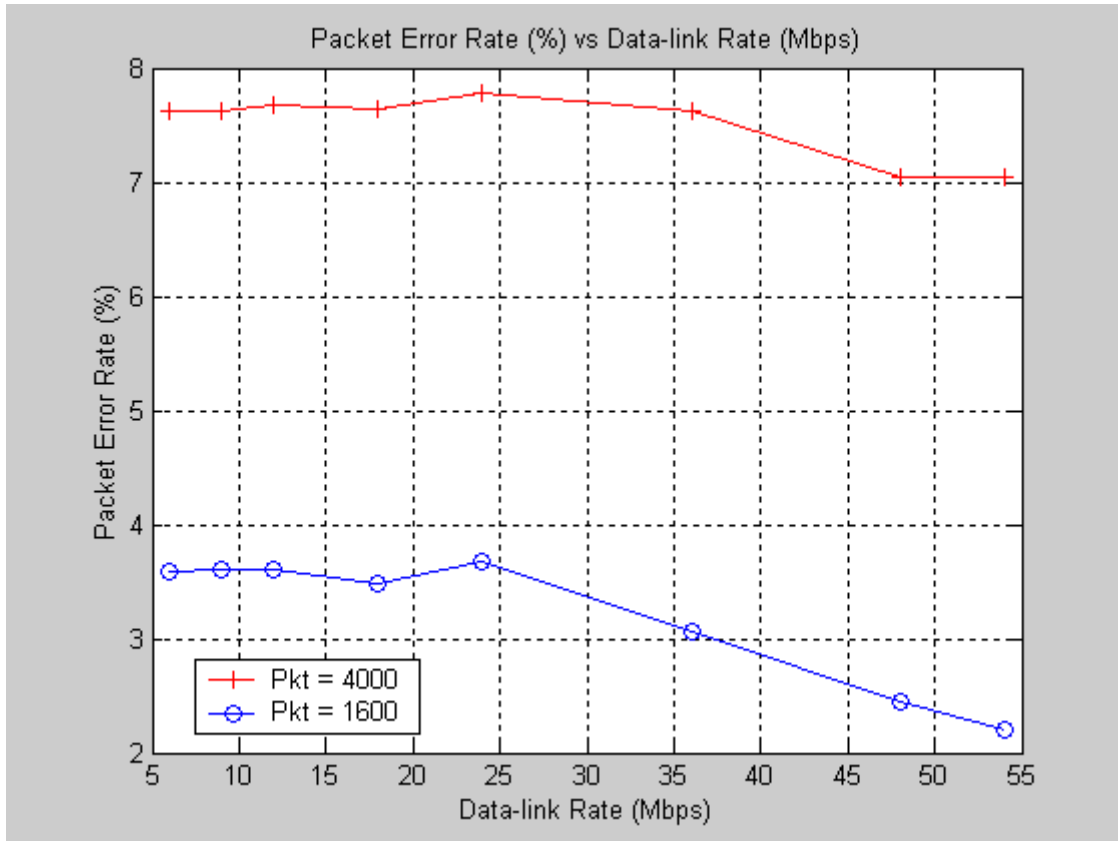


Figure 29. Plot of the Effect of Packet Length on Measured Packet Error Rate (Cisco – Land)

The packet length of 1,600 bytes is the minimum setting for the Cisco Aironet 1400 wireless bridge. This packet length setting is closest to that of the Ethernet (1,500 bytes). The packet length of 4,000 bytes is the maximum setting for the bridge. The graph in Figure 28 shows that the data throughput for both packet lengths were similar. However, in Figure 29, the packet error rate for a packet length of 1,600 bytes was substantially lower than that for a packet length of 4,000 bytes.

This observation is consistent with our theory that a longer packet contains more data bits and is therefore expected to face more errors. Moreover, with the same error correction technique employed, longer packets also faced lower probability of success. Despite the higher packet error rate observed, the data throughput was maintained. This was so because each packet was capable of carrying more data bits for the same overhead.

9. Summary

From the field-testing in a land environment, the following conclusions were made:

- A range of three kilometers was achieved at the data-link rate of 54 Mbps.
- The maximum measured data throughput achieved at the data-link rate of 54 Mbps was 20.80 Mbps, with 3.37% PER.
- The measured data throughput decreased with increasing range.
- The measured PER increased with increasing range.
- The average measured data throughput for 6, 9, 12, 18, 24, 36, 48 and 54 Mbps was 2.69, 4.78, 5.56, 8.19, 10.27, 14.27, 18.04 and 19.84 Mbps, respectively.
- Using the WEP (40-bit or 128-bit) did not degrade the performance of the IEEE 802.11a network.
- The packet length did not affect the data throughput, but it affected the PER. A longer packet resulted in higher PER.

D. OVER-WATER ENVIRONMENT TESTING

1. Test Plan

The test plan for an over-water environment is shown in Figure 30 – the Del Monte beach, the Best Western at the Beach, the Bay Street, and the Sandcity along the coast of Monterey Bay. The wharf was selected as the root wireless bridge because it protrudes out to sea. This allows field-testing over as much water body as possible. Both wireless bridges were at an antenna height of two meters. The only available tall building near the wharf is the Marriott Hotel. As this is a private hotel, it was not selected as a test point for the root wireless bridge.

Owing to the low antenna height at both ends of the wireless bridge, the range performance was expected to be less. Therefore, the furthest test point selected was at a range of 3.85 km. The nearest test point was at a distance of 1.75 km, as no other vehicle-accessible test points could be located at a distance closer than 1.75 km. Moreover, the test points were selected with minimum human traffic. At an antenna height of two meters, human traffic would most likely affect the field-testing data collected.

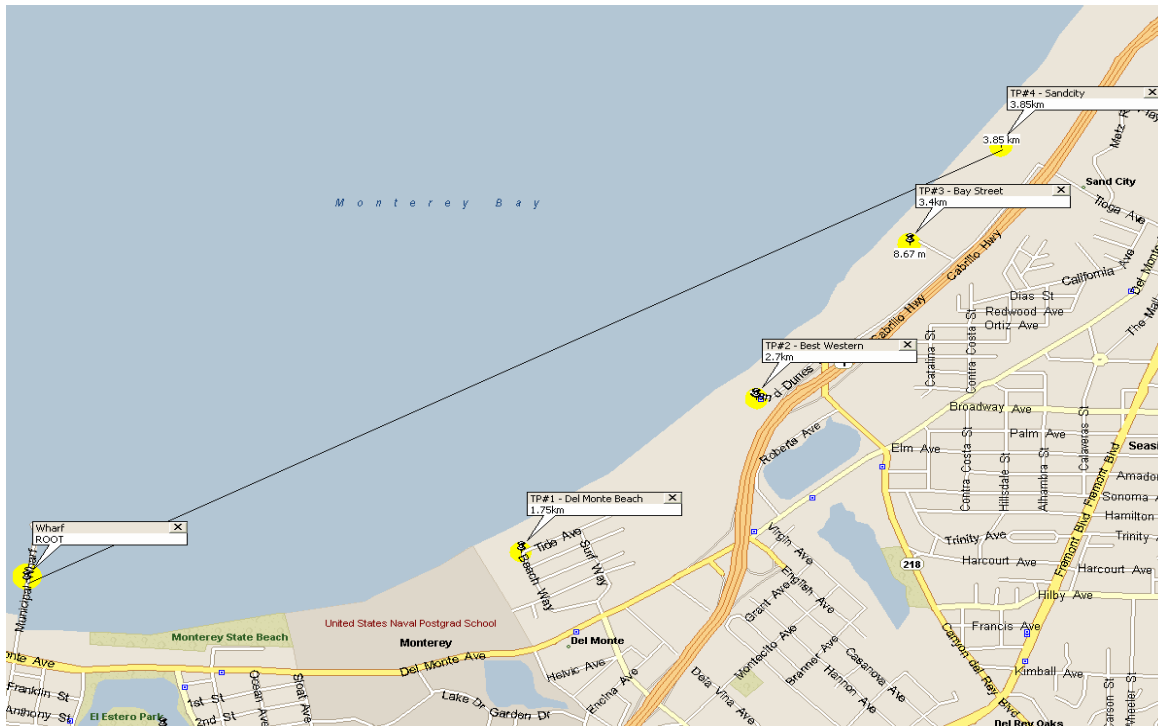


Figure 30. Test Points (Water)

2. Overall Performance Data

The performance data for the Cisco Aironet 1400 wireless bridge in an over-water environment is summarized in Table 16. The received signal strength, the maximum data-link rate, the maximum data throughput, and the average PER were measured and recorded at each test point.

Test Point	Range (m)	Received Signal Strength (dBm)	Maximum Data-link Rate (Mbps)	Maximum Data Throughput (Mbps)	Average PER (%)
1	1,750	−63	54	19.42	6.25
2	2,700	−72	24	10.03	9.23
3	3,400	−76	18	7.86	9.28
4	3,850	−79	12	5.05	15.04

Table 16. Overall Measured Performance Data in a Water Environment
(Cisco)

3. Received Signal Strength

Figure 31 shows the plot of the measured received signal strength versus range. The measured received signal strength decreased with increasing range.

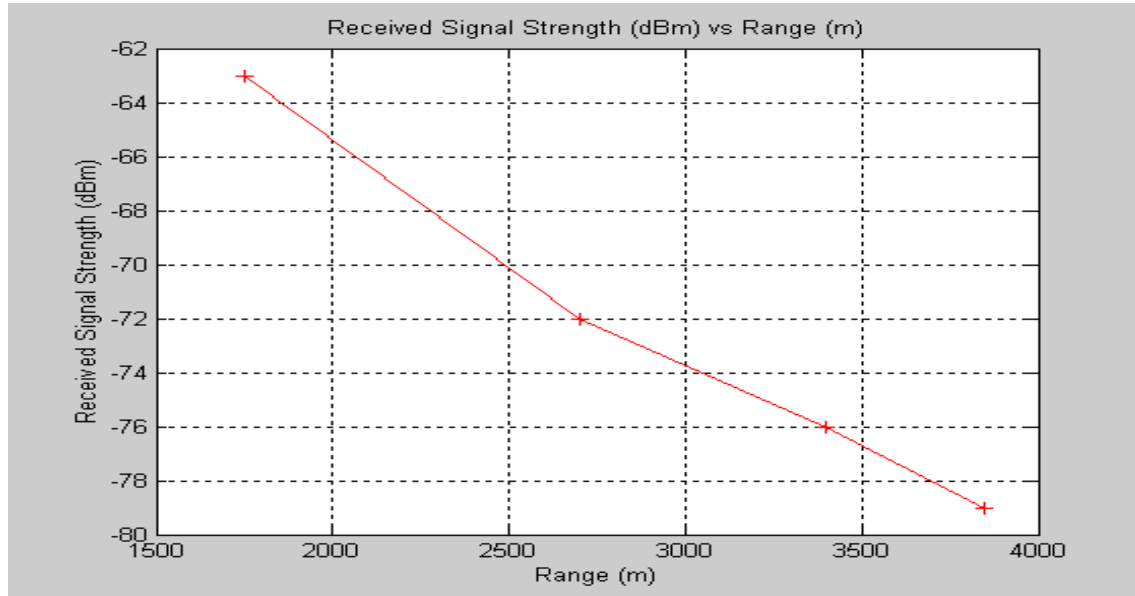


Figure 31. Measured Signal Strength at Receiver versus Range (Cisco – Water)

4. Maximum Data-link Rate

Figure 32 shows the plot of the maximum measured data-link rate achieved versus range at the different test points. Only test point one recorded a successful link at the data-link rate of 54 Mbps. By varying the power setting, the field-testing showed that the receiver sensitivity was approximately 5 dBm lower than its specifications (Table 4).

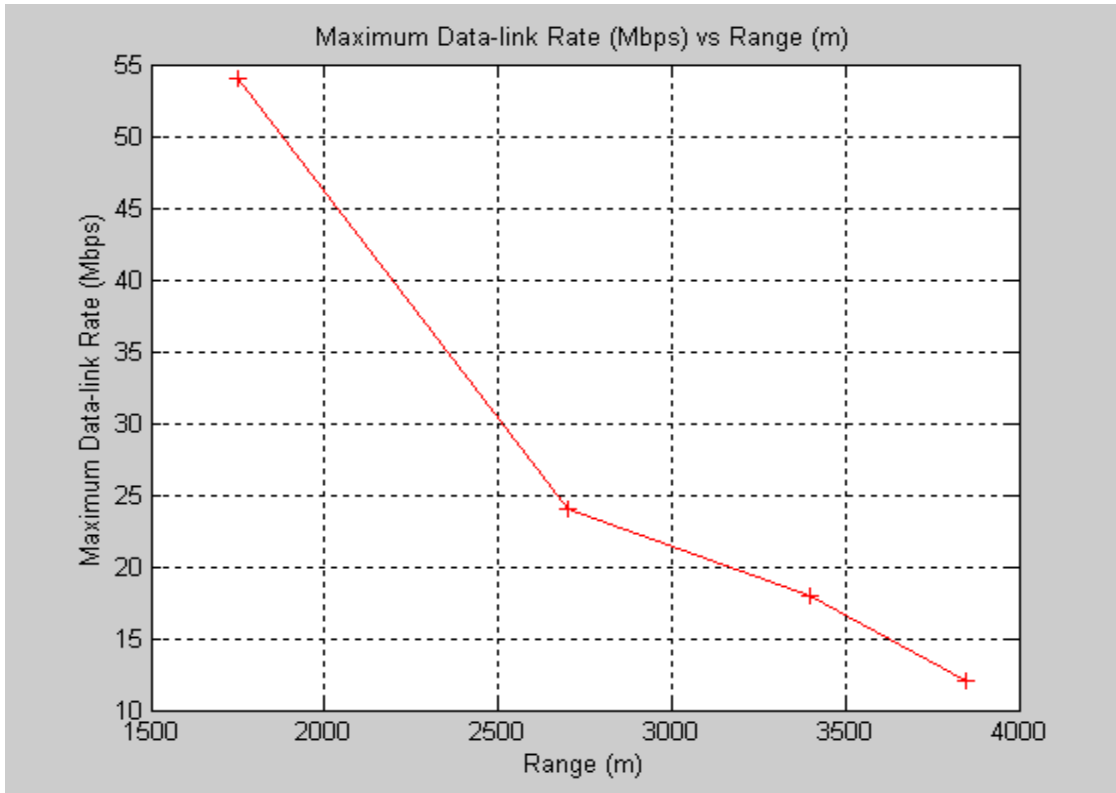


Figure 32. Maximum Measured Data-link Rate versus Range (Cisco – Water)

5. Maximum Data Throughput and Packet Error Rate

Figures 33 and 34 show the maximum measured data throughput and measured average packet error rate versus range at all four test points. Figure 33 shows the maximum data throughput decreased with increasing range. This was consistent with the maximum data-link rate decreasing with increasing range. Figure 34 shows that the packet error rate increased with increasing range.

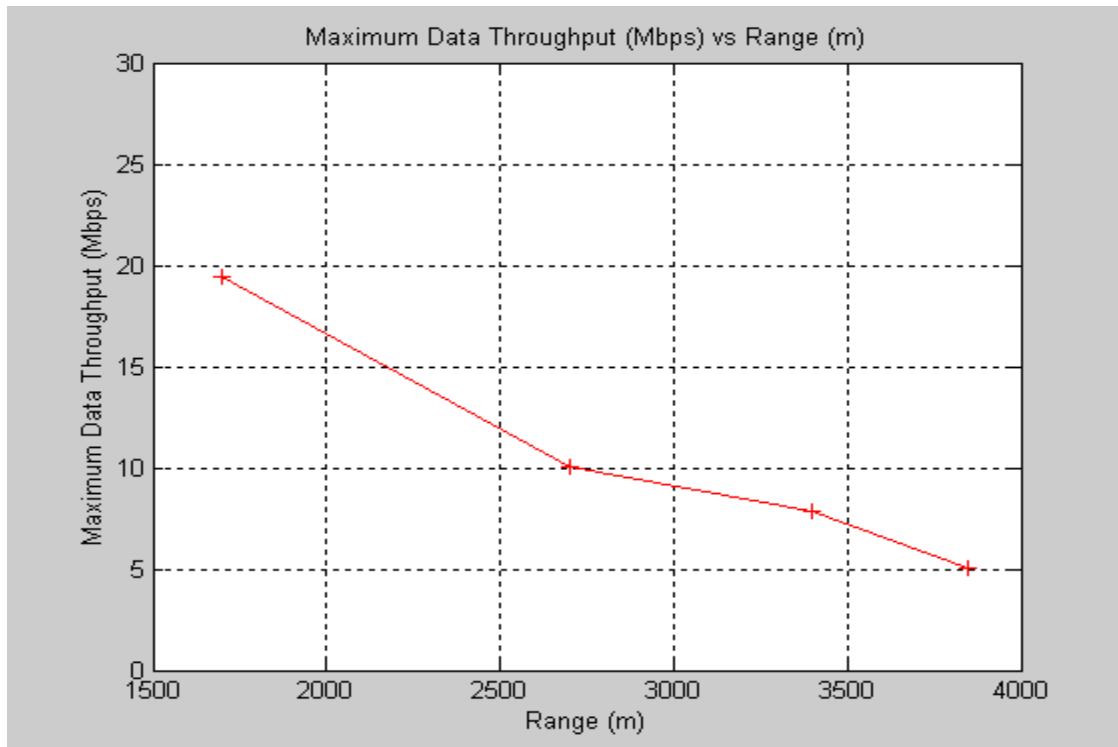


Figure 33. Maximum Measured Data Throughput versus Range (Cisco – Water)

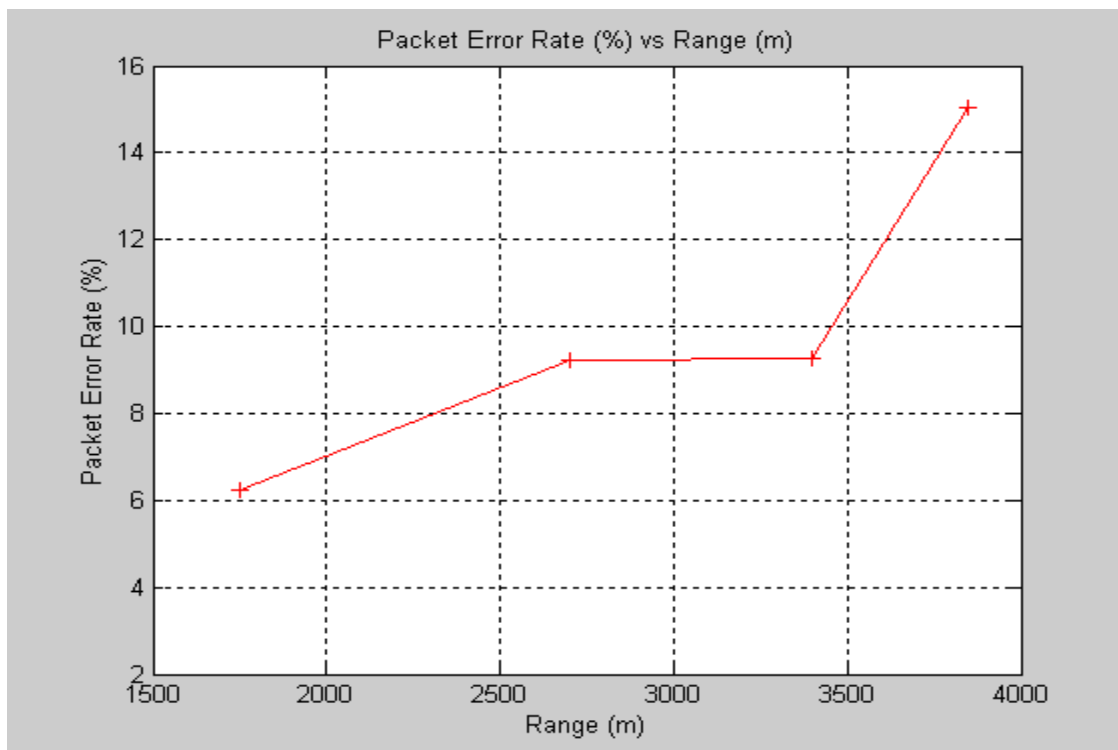


Figure 34. Measured Average Packet Error Rate versus Range (Cisco – Water)

6. Data Throughput versus Data-link Rate

Table 17 consolidates the measured performance data collected on data throughput achieved over the entire range of data-link rate (6 to 54 Mbps) at all four test points. Figure 35 plots the measured data throughput achieved over the entire range of data-link rates (6 to 54 Mbps). Test points one to four are plotted in red, blue, magenta and green, respectively.

Test Point	Range (m)	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
		6	9	12	18	24	36	48	54
1	1750	2.78	4.85	5.76	8.45	10.78	14.88	18.28	19.42
2	2700	2.65	4.76	5.56	8.16	10.03	-	-	-
3	3400	2.65	4.70	5.46	7.86	-	-	-	-
4	3850	2.42	4.38	5.05	-	-	-	-	-
Average Data Throughput		2.63	4.67	5.46	8.16	10.41	14.88	18.28	19.42

Table 17. Measured Data Throughput versus Data-link Rates at Various Ranges (Cisco – Water)

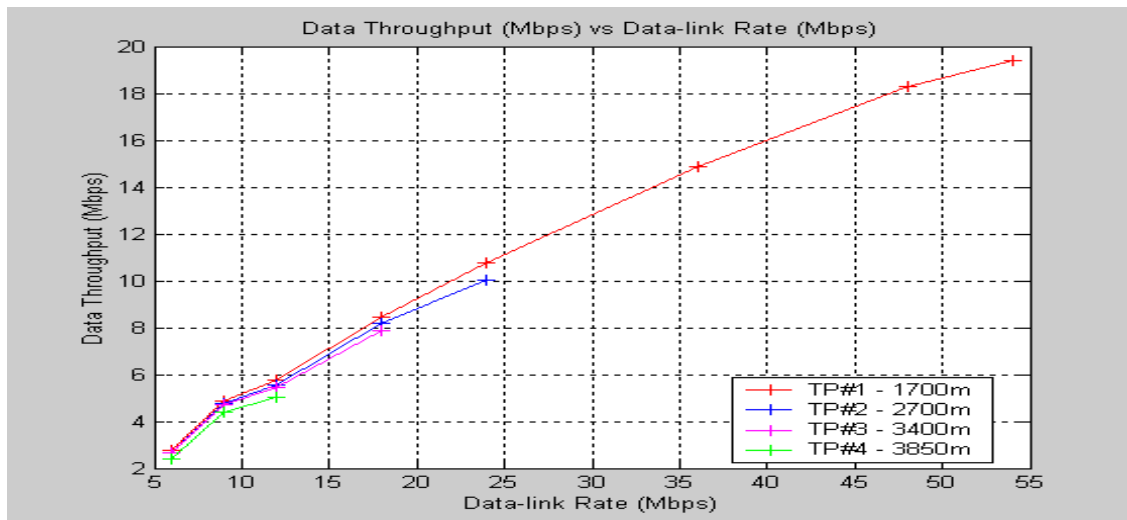


Figure 35. Plot of the Measured Data Throughput versus Data-link Rates at Various Ranges (Cisco – Water)

Figure 35 shows that data throughput degraded slightly as the distance increased. Although the values were similar at lower data-link rates, at a 24-Mbps data-link rate the degradation increased. There was no comparison at a data-link rate above 24 Mbps. However, based on the graphs and values obtained from the land environment testing, it was assessed that a higher deviation of data throughput occurred at a higher data-link rate. The average measured data throughput achieved for 6, 9, 12, 18, 24, 36, 48 and 54 Mbps was 2.63, 4.67, 5.46, 8.16, 10.41, 14.88, 18.28 and 19.42 Mbps, respectively. These values were similar to those obtained for the land environment.

7. Summary

From the field-testing in an over-water environment, the following conclusions were made:

- A maximum range of 1.75 km was achieved at the data-link rate of 54 Mbps.
- The maximum measured data throughput achieved at the data-link rate of 54 Mbps was 19.42 Mbps, with 6.25% PER.
- The wireless bridge's receiver sensitivity was approximately 5 dBm lower than the specification stated in Table 4.
- The measured data-link rate and data throughput decreased with increasing range.
- The measured PER increased with increasing range.
- The average measured data throughput for 6, 9, 12, 18, 24, 36, 48 and 54 Mbps was 2.63, 4.67, 5.46, 8.16, 10.41, 14.88, 18.28 and 19.42 Mbps, respectively.

E. VEGETATION ENVIRONMENT TESTING

1. Test Plan

Based on the operational scenario of ground troops being within 100 m of the APC, a site in La Mesa was selected with thick vegetation. Although the composition of the vegetation could be different in actual deployment, this site provided a fair assessment on the performance limitation of IEEE 802.11a signals in vegetation. Figure 36 shows a picture of the test site. The test was performed without LOS and with an antenna height of two meters on both sides of the wireless bridge.



Figure 36. Picture of the Vegetation Environment

2. Overall Performance Data

The performance data for the Cisco Aironet 1400 wireless bridge in vegetation is summarized in Table 18. The received signal strength, the maximum data-link rate, the maximum data throughput, and the average PER were measured and recorded at each test point.

Test Point	Range (m)	Received Signal Strength (dBm)	Maximum Data-link Rate (Mbps)	Maximum Data Throughput (Mbps)	Average PER (%)
1	25	-41	54	20.93	3.08
2	50	-49	54	20.78	3.18
3	75	-57	54	20.15	3.89
4	100	-67	48	19.70	5.84

Table 18. Overall Measured Performance Data in Vegetation (Cisco)

3. Received Signal Strength

Figure 37 shows the plot of the measured received signal strength versus range at all test points. The measured received signal strength decreased with increasing range.

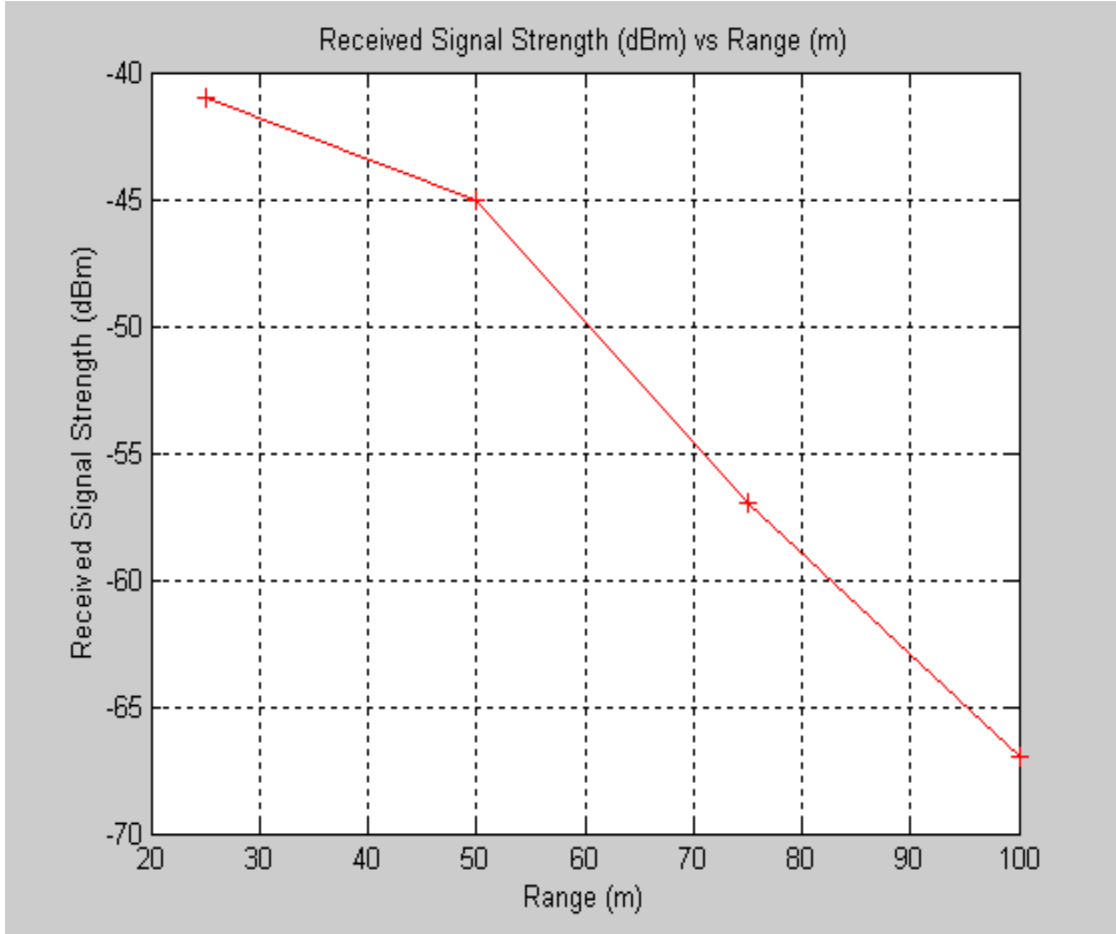


Figure 37. Measured Signal Strength at Receiver versus Range (Cisco – Vegetation)

4. Maximum Data-link Rate

Figure 38 shows the plot of the maximum measured data-link achieved versus range at the different test points. The data-link rate of 54 Mbps was maintained up to a distance of 75 m.

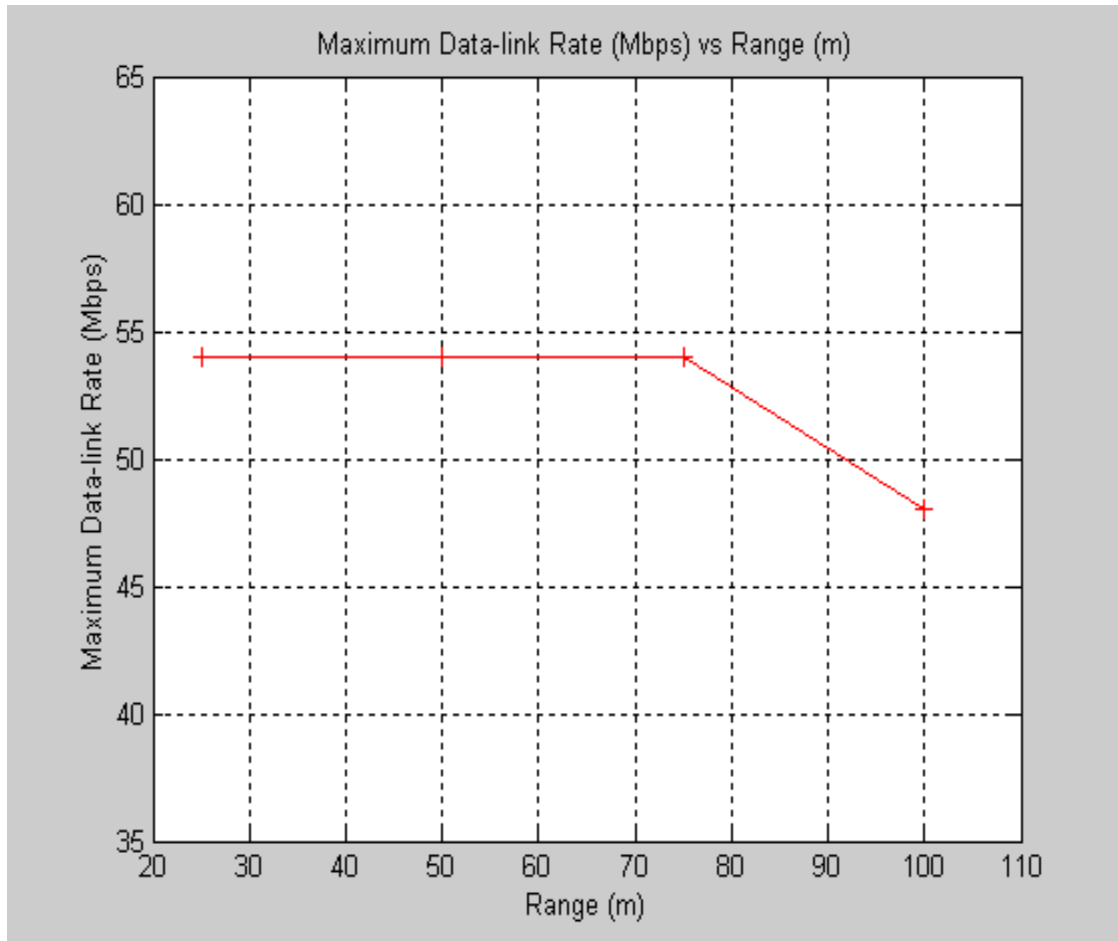


Figure 38. Maximum Measured Data-link Rate versus Range (Cisco – Vegetation)

5. Maximum Data Throughput and Packet Error Rate

Figures 39 and 40 show the maximum measured data throughput and measured average packet error rate versus range at all four test points. From Figure 39, it was observed that the maximum data throughput decreased with increasing range. This was consistent with the maximum data-link rate decreasing with increasing range. From Figure 40, it was also observed that the packet error rate increased with increasing range.

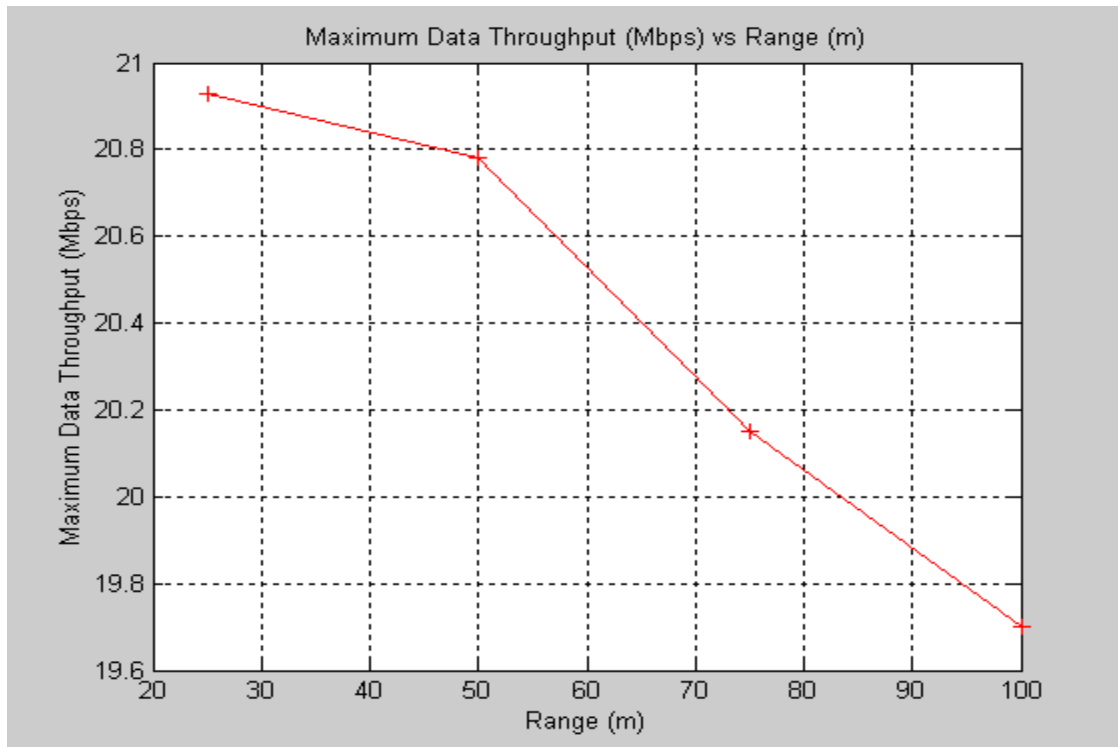


Figure 39. Maximum Measured Data Throughput versus Range (Cisco – Vegetation)

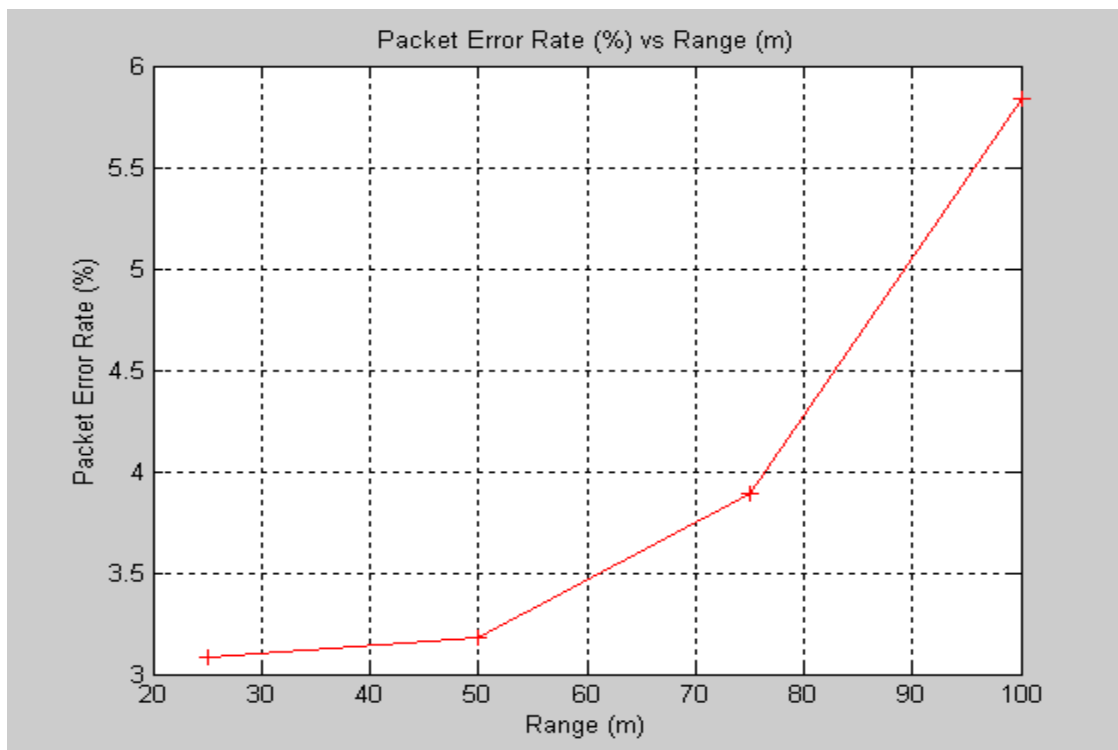


Figure 40. Measured Average Packet Error Rate versus Range (Cisco – Vegetation)

6. Data Throughput versus Data-link Rate

Table 19 consolidates the measured performance data collected on the data throughput achieved over the entire range of the data-link rate (6 to 54 Mbps) at all four test points. Figure 41 plots the measured data throughput achieved over the entire range of the data-link rate (6 to 54 Mbps). Test points one to four are plotted in red, blue, magenta and green, respectively.

Test Point	Range (m)	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
		6	9	12	18	24	36	48	54
1	25	2.81	5.13	5.85	8.80	10.89	15.04	19.85	20.93
2	50	2.73	4.96	5.85	8.68	10.65	14.73	19.60	20.78
3	75	2.65	4.82	5.78	8.63	10.57	14.52	19.42	20.15
4	100	2.61	4.76	5.52	8.50	10.33	14.50	19.15	-
Average Data Throughput		2.70	4.92	5.75	8.65	10.61	14.70	19.51	20.62

Table 19. Measured Data Throughput versus Data-link Rates at Various Ranges (Cisco – Vegetation)

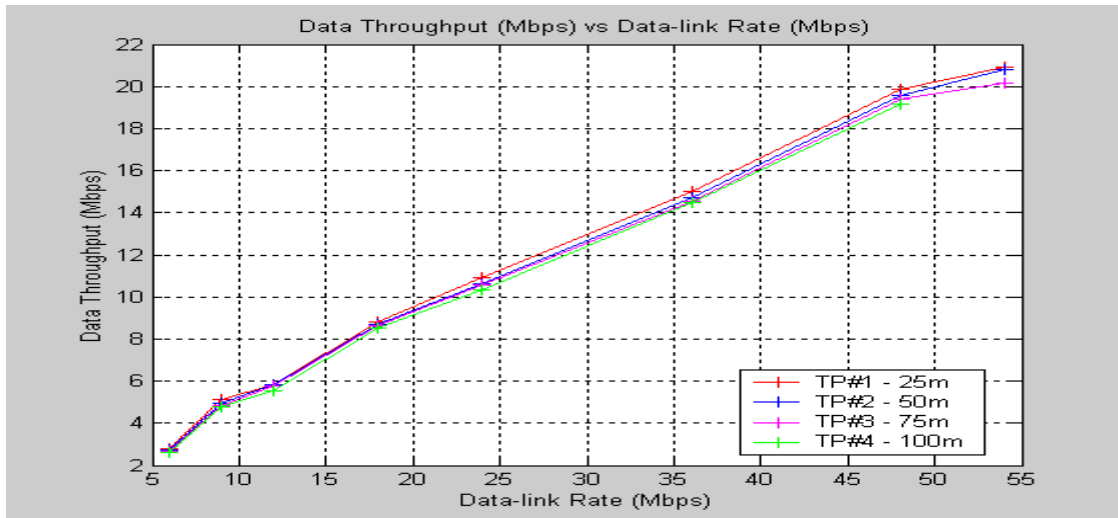


Figure 41. Plot of the Measured Data Throughput versus Data-link Rates at Various Ranges (Cisco – Vegetation)

The graph in Figure 41 shows that measured data throughput degraded slightly as distance increased. In vegetation, the data throughput at a higher data-link rate degraded less. This could be due to the proximity of the test points to the root wireless bridge. The average measured data throughput achieved for 6, 9, 12, 18, 24, 36, 48 and 54 Mbps was 2.70, 4.92, 5.75, 8.65, 10.61, 14.70, 19.51 and 20.62 Mbps, respectively.

7. Summary

From the field-testing conducted in vegetation, the following conclusions were made:

- A maximum range of 75 m was achieved at the data-link rate of 54 Mbps.
- The maximum measured data throughput achieved at the data-link rate of 54 Mbps was 20.93 Mbps, with 3.08% PER.
- The measured data throughput decreased with increasing range.
- The measured PER increased with increasing range.
- The average measured data throughput for 6, 9, 12, 18, 24, 36, 48 and 54 Mbps was 2.70, 4.92, 5.75, 8.65, 10.61, 14.70, 19.51 and 20.62 Mbps, respectively.

F. CHAPTER SUMMARY

This chapter presented the laboratory setup and testing, the generation of the test plans, the collection of data from field-testing, and the performance analysis. The signal attenuation, the packet error rate (PER), and the effective data throughput under all three operational environments – land, water, and vegetation – were investigated.

The next chapter presents the field-testing data for Proxim Tsunami MP.11a wireless system and its performance analysis.

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VI. PROXIM TSUNAMI MP.11A WIRELESS SYSTEM'S TESTING, RESULTS AND DISCUSSIONS

A. CHAPTER OVERVIEW

This chapter presents the laboratory setup and testing, and the collection of data from field-testing for the Proxim Tsunami MP.11a wireless system. A performance analysis was conducted on the field data collected to study the signal attenuation, the Packet Error Rate (PER), and the effective data throughput under all three operational environments – land, water, and vegetation.

The same test plans for the Cisco Aironet 1400 wireless bridge were used, but the effect of the use of encryption on performance was studied under laboratory conditions to minimize the amount of time required for field-testing. This was to minimize the disturbance to local residents (surrounding NPS) and due to the limited power of the portable power pack. This change did not affect the performance study. The effect of using encryption on performance was also repeated for the Cisco Aironet 1400 wireless bridge using the laboratory setup with similar results observed as for outdoors. The effect of packet length variation could not be conducted as the packet size is fixed at 1,504 bytes.

B. LABORATORY SETUP AND TESTING

The Proxim Tsunami MP.11a wireless system was set up under laboratory conditions to ensure the proper integration and functionality between the supporting hardware and software with the wireless system, prior to field-testing.

Figure 42 shows the laboratory setup of the Proxim Tsunami MP.11a wireless system. The equipment on the left of the figure represents the Base Station Unit (BSU), which is similar in function to the root bridge in the Cisco Aironet 1400 wireless bridge. The equipment on the right represents the Subscriber Unit (SU) or non-root bridge. Both the BSU and SU are made up of a 15-dBi directional antenna, a radio, a notebook, a Xantrex Power Pack, a RF cable, an Ethernet cable and two power cables. The BSU and SU were placed six meters apart, with power set to the lowest of “Minimum.” This translates to a 10-dBm reduction in power compared to the normal power setting specified in

Table 8. The frequency channel used was 5.805 GHz. This was consistent with the Cisco Aironet 1400 wireless bridge.

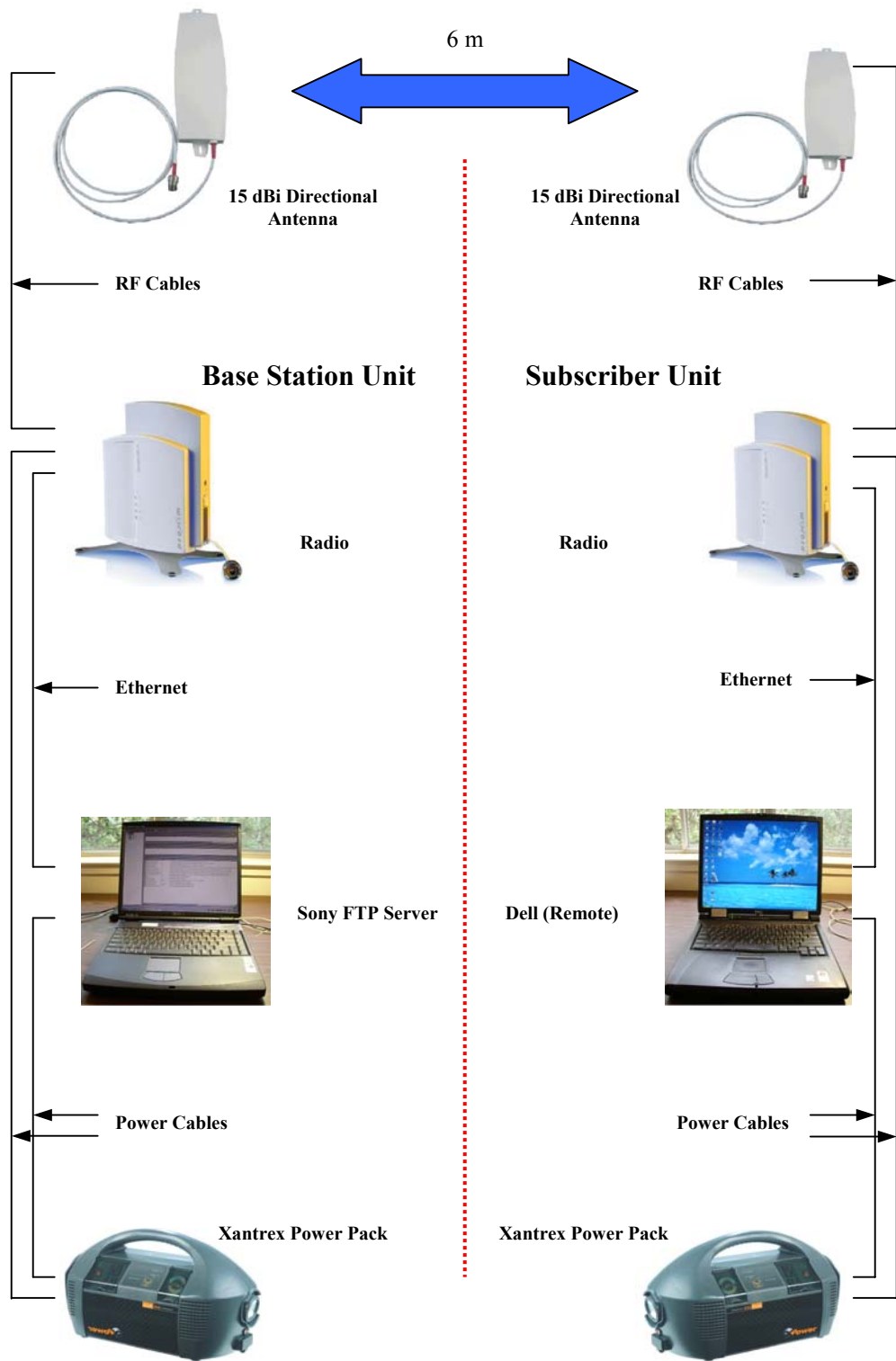


Figure 42. Proxim Tsunami MP.11a Wireless System Laboratory Setup

The entire range of data-link rate from 6 to 54 Mbps was tested. Figure 43 shows the screen capture of the setting of data-link rate. A particular data-link rate was selected by clicking on the respective icon. A file size of approximately 40 Mbytes, containing zipped pictures, was used to observe the performance of the Proxim Tsunami MP.11a wireless system.

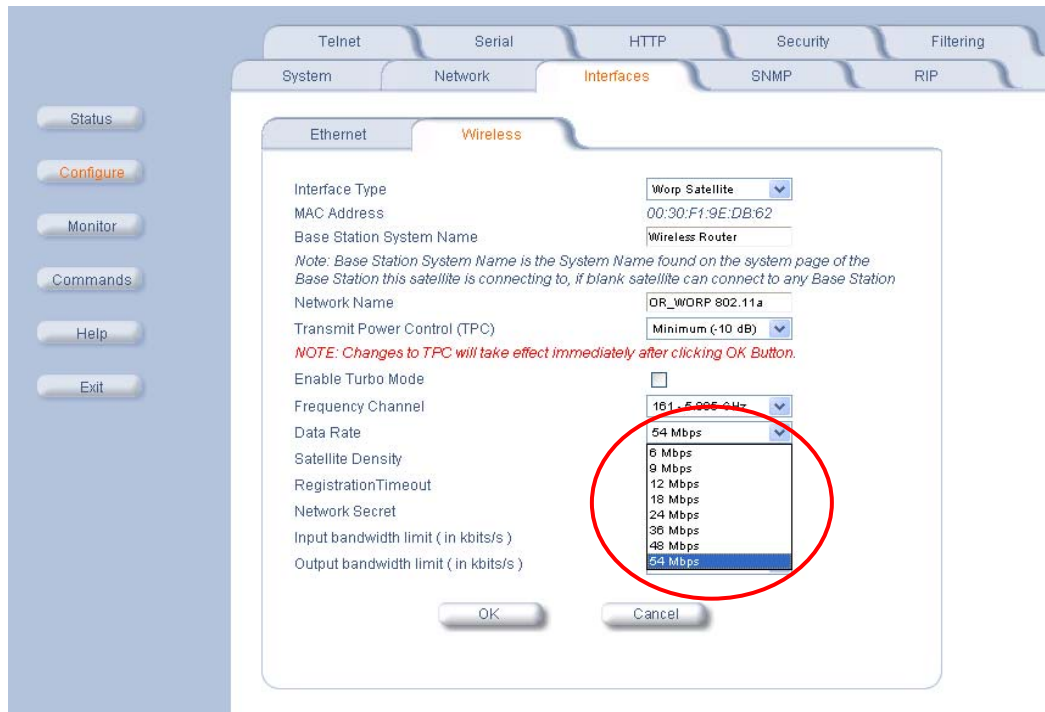


Figure 43. Screen Capture of the Setting of Data-link Rate (Proxim)

1. Effect of Encryption on Performance

The Proxim Tsunami MP.11a offers three encryption methods – 64-bit WEP, 128-bit WEP, and 128-bit Advanced Encryption System (AES). The 64-bit WEP is identical to the 40-bit WEP. Just like the 128-bit WEP, the additional 24 bits are needed for the initialization vector. Table 20 shows the measured data throughput achieved for the respective encryption methods used at various data-link rates. Figure 44 shows the plot, where no WEP, 64-bit WEP, 128-bit WEP, and 128-bit AES are plotted in red, blue, ma-

genta and green, respectively. At the data-link rate of 54 Mbps, the file transfer could not be completed, therefore a data throughput of 0 Mbps was recorded.

Encryption	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
	6	9	12	18	24	36	48	54
No	2.87	5.36	5.87	8.52	9.65	10.94	2.63	0
64-Bit WEP	2.80	5.37	5.82	8.25	9.70	10.75	2.58	0
128-Bit WEP	2.86	5.32	5.77	8.21	9.51	10.78	2.66	0
128-Bit AES	2.84	5.27	5.85	8.17	9.61	10.47	2.33	0
Average Data Throughput	2.84	5.33	5.83	8.29	9.62	10.74	2.55	0

Table 20. Effect of Encryption on Measured Data Throughput
(Proxim – LAB)

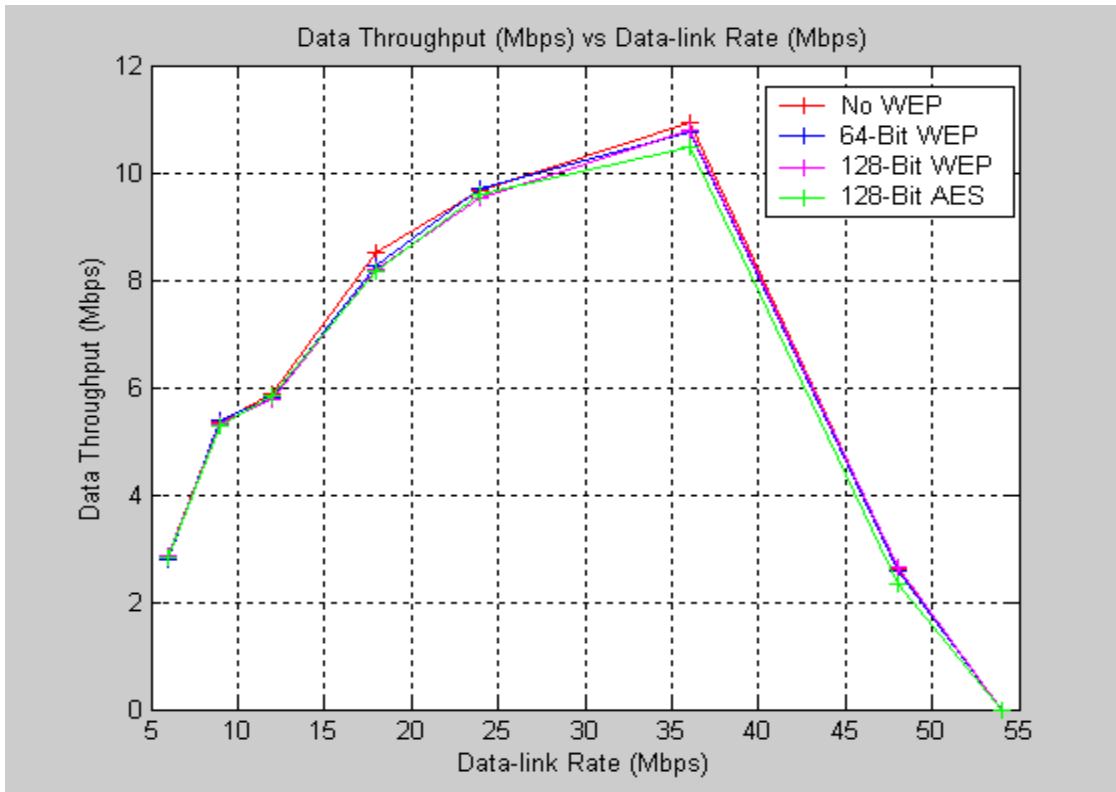


Figure 44. Plot of the Effect of Encryption on Measured Data Throughput
(Proxim – LAB)

Figure 44 shows that the measured data throughput for each data-link rate setting was not affected by the use of encryption. The average measured data throughput for the data-link rate of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps was 2.84, 5.33, 5.83, 8.29, 9.62, 10.74, 2.55 and 0 Mbps. It was observed that the maximum data throughput of approximately 11 Mbps was achieved at the data-link rate of 36 Mbps. At the data-link rate of 48 Mbps, a data throughput of approximately 2.6 Mbps was obtained. Although the link was established at the data-link rate of 54 Mbps, the transfer of the 40-Mbyte file could not be completed.

Table 21 shows the measured packet error rate recorded when encryption was used at various data-link rates. Figure 45 shows the plot, where no WEP, 64-bit WEP, 128-bit WEP, and 128-bit AES are plotted in red, blue, magenta and green, respectively. At the data-link rate of 54 Mbps, a PER of 100 % was recorded, as the file transfer could not be completed.

Encryption Method	Packet Error Rate (%) at Varying Data-link Rates (Mbps)							
	6	9	12	18	24	36	48	54
No	0	0	0	0	0	0.15	10.45	100.00
64-Bit WEP	0	0	0	0	0	0.00	10.79	100.00
128-Bit WEP	0	0	0	0	0	0.00	10.61	100.00
128-Bit AES	0	0	0	0	0	0.09	11.05	100.00
Average PER	0	0	0	0	0	0.06	10.73	100.00

Table 21. Effect of Encryption on Measured Packet Error Rate
(Proxim – LAB)

Figure 45 shows the use of encryption did not affect the Packet Error Rate (PER). Up to the data-link rate of 36 Mbps, the PER was small. However, at the data-link rate of 48 Mbps and 54 Mbps, the PER was 10.73% and 100%, respectively. This was consistent with the data throughput observed in Figure 44. The main reason for this is that both data-link rates use the modulation technique, 64-QAM. Despite QAM's higher data

throughput, it is very sensitive to noise and multipath fading effects, leading to high PER. As packets were re-sent many times, the effective data throughput was significantly reduced. At the data-link rate of 54 Mbps, the PER was so high that the file transfer could not be completed.

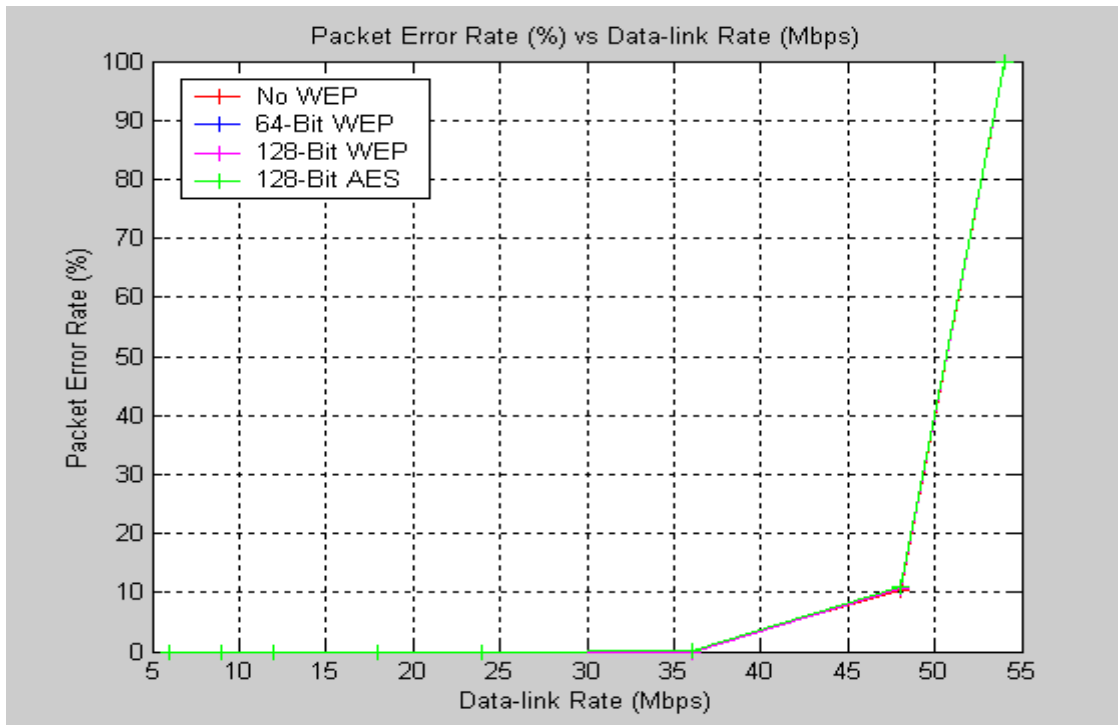


Figure 45. Plot of the Effect of Encryption on Measured Packet Error Rate (Proxim – LAB)

In summary, this testing shows that establishing a communication link at a high data-link rate does not necessarily translate to a higher data throughput. This is only true if the equipment is adequately designed to reduce the effects of noise and multipath.

C. LAND ENVIRONMENT TESTING

1. Overall Performance Data

The same test points as the Cisco Aironet 1400 wireless bridge were used. The performance data for the Proxim Tsunami MP.11a wireless system in a land environment

is summarized in Table 22. The received signal strength in dBm was converted from the RSSI reading recorded (Received Signal Strength [dBm] = RSSI – 92). The maximum data-link rate, the maximum data throughput, and the average Packet Error Rate (PER) were measured and recorded from the FTP server software and the Proxim Tsunami MP.11a wireless system Graphical User Interface (GUI).

Test Point	Range (m)	Received Signal Strength (dBm)	Maximum Data-link Rate (Mbps)	Maximum Data Throughput (Mbps)	Average PER (%)
1	300	– 55	54	10.85	0.12
2	700	– 61	54	10.35	0.16
3	1,000	– 65	48	9.68	0.22
4	1,600	– 67	48	9.25	0.24
5	2,350	– 75	36	8.14	0.39
6	3,000	– 79	24	7.73	0.48

Table 22. Overall Measured Performance Data in a Land Environment (Proxim)

In Table 22, the maximum measured data throughput for all the test points (less test point six) were registered at the data-link rate of 36 Mbps. Although communication links were established for both 48 and 54 Mbps, the packet error rates were very high. The packet error rate was so high that file transfer could not be completed. The average packet error rate disregarded these high packet error rates. This led to the conclusion that the Proxim Tsunami MP.11a is not well designed for 64-QAM (48 and 54 Mbps), which is consistent with its specification of optimal performance achieved at 36 Mbps (16-QAM).

2. Received Signal Strength

The measured received signal strength versus range is plotted in Figures 46 at all test points. The measured received signal strength decreased with increasing range.

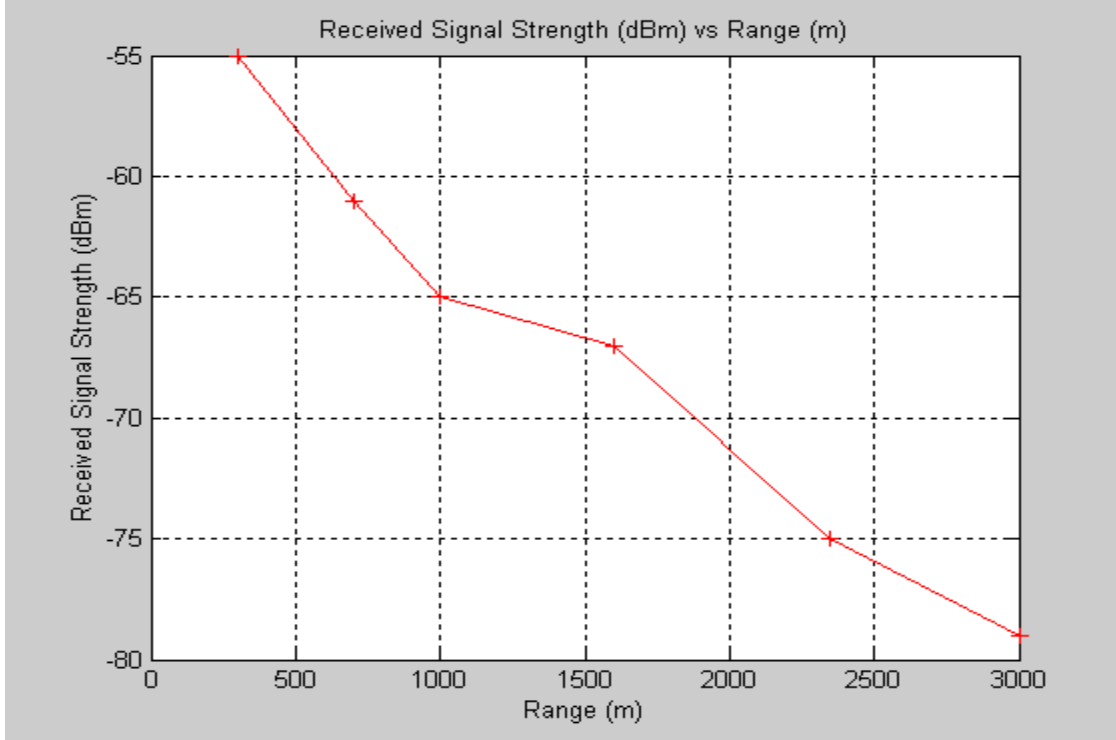


Figure 46. Measured Signal Strength at Receiver versus Range (Proxim – Land)

3. Optimal Data-link Rate

From the data collected for the laboratory testing and the land environment field-testing, it was determined that optimal performance was achieved at the data-link rate of 36 Mbps.

4. Maximum Data Throughput and Packet Error Rate

Figures 47 and 48 show the maximum measured data throughput and measured average packet error rate versus range at all six test points. Figure 48 shows that the packet error rate increased with increasing range. This in turn led to a lower data throughput observed in Figure 47. Thus the maximum data throughput for the optimal data-link rate of 36 Mbps at 2.35km was 8.14 Mbps and its average packet error rate was 0.39%.

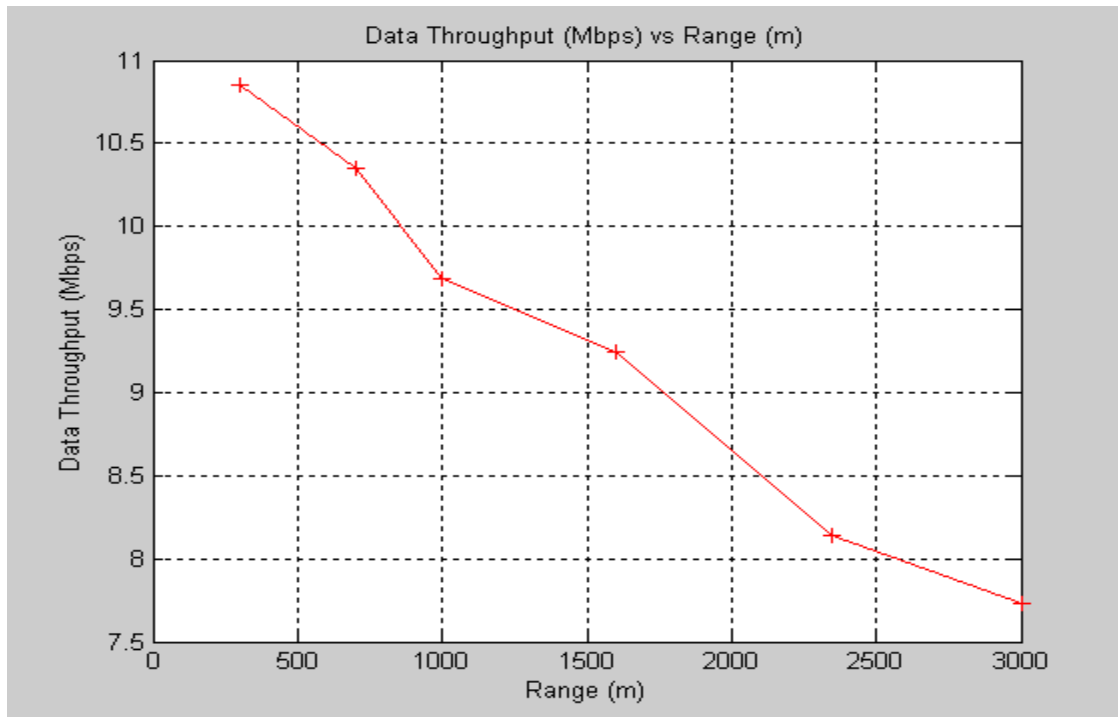


Figure 47. Maximum Measured Data Throughput versus Range (Proxim – Land)

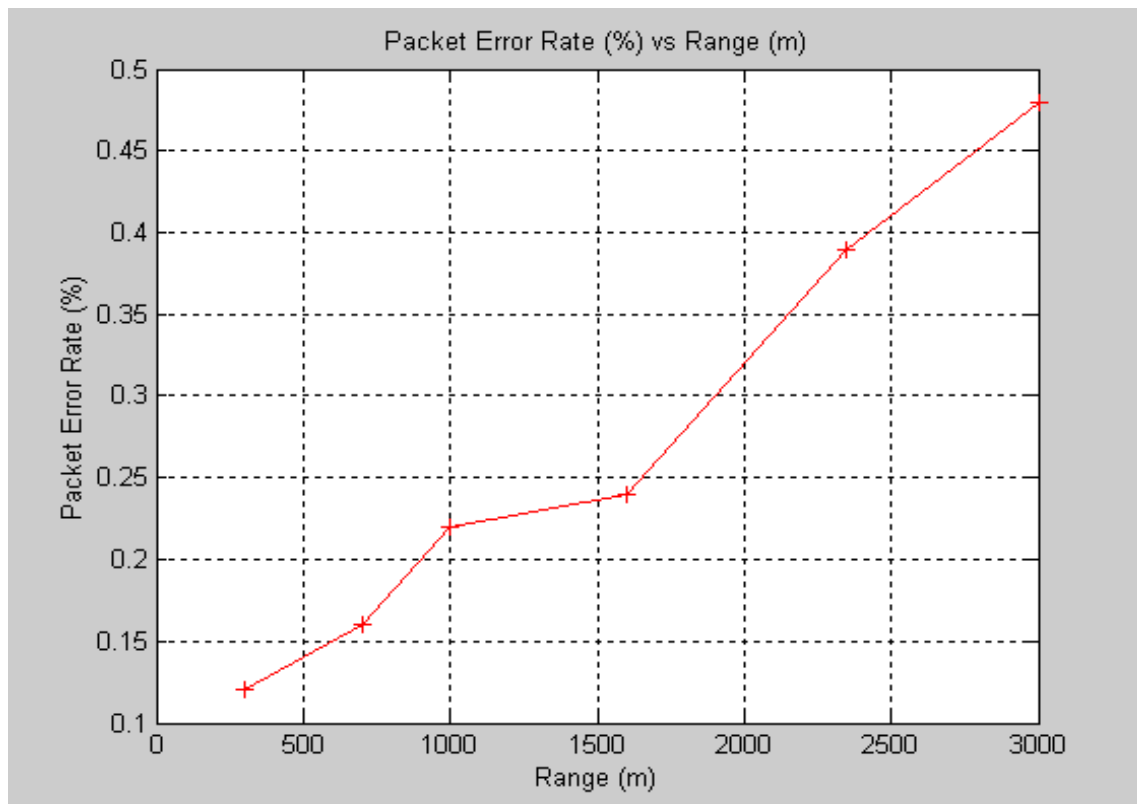


Figure 48. Measured Average Packet Error Rate versus Range (Proxim – Land)

5. Data Throughput versus Data-link Rate

Table 23 consolidates the measured performance data collected on the data throughput achieved over the entire range of the data-link rate (6 to 54 Mbps). These performance data were collected for all six test points. In Table 24, the “-” represents no communication link established, while “X” represents that the file transfer was not successful or the data throughput was very low.

Figure 49 plots the measured data throughput achieved over the entire range of data-link rate (6 to 54 Mbps). Test points one to six are plotted in red, blue, magenta, green, black and light blue, respectively. The graph shows that the data throughput degraded as distance increased. The degradation was more severe than that observed for the Cisco Aironet 1400 wireless bridge. The average measured data throughput achieved for 6, 9, 12, 18, 24 and 36 Mbps was 2.55, 4.67, 5.14, 7.45, 8.50 and 9.65 Mbps, respectively.

Test Point	Range (m)	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
		6	9	12	18	24	36	48	54
1	300	2.73	5.07	5.49	8.09	9.25	10.85	X	X
2	700	2.62	4.87	5.36	7.82	8.94	10.35	X	-
3	1,000	2.54	4.72	5.10	7.44	8.61	9.68	X	-
4	1,600	2.52	4.55	5.03	7.35	8.54	9.25	X	-
5	2,350	2.47	4.47	4.94	7.17	7.90	8.14	-	-
6	3,000	2.44	4.34	4.91	6.85	7.74	-	-	-
Average Data Throughput		2.55	4.67	5.14	7.45	8.50	9.65	-	-

Table 23. Measured Data Throughput versus Data-link Rates at Various Ranges (Proxim – Land)

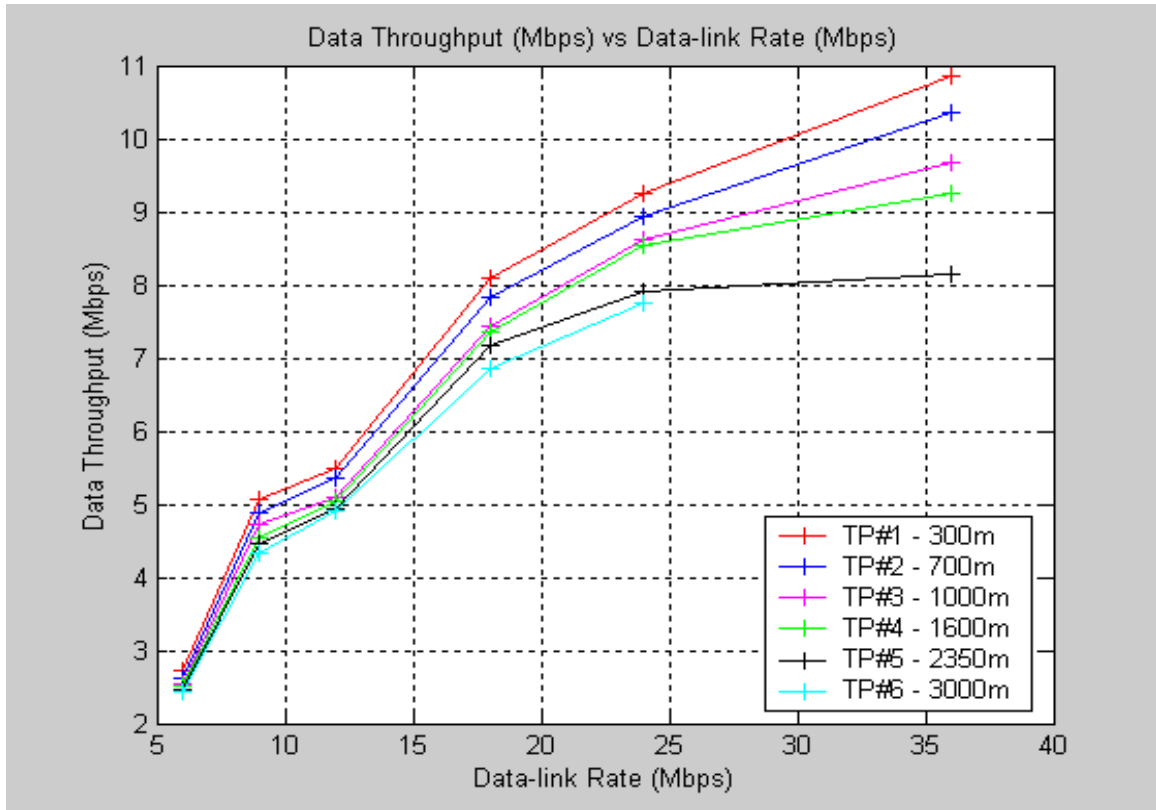


Figure 49. Plot of the Measured Data Throughput versus Data-link Rates at Various Ranges (Proxim – Land)

At a lower data-link rate, the data throughput achieved for all six test points was closer to one other. At a higher data-link rate, the deviation between the data throughput recorded at different test points increased. One possible reason for this is that at a higher data-link rate, the modulation technique used is QAM, which is more prone to noise or interference. Therefore, over a larger range, the degradation is more severe. An important point to note is that file transfer at the data-link rate of 48 and 54 Mbps was either extremely slow (e.g., 0.48 Mbps) or could not be completed. This led to the conclusion that the Proxim Tsunami MP.11a performed well only at the data-link rate of 36 Mbps and below. This observation could be due to the lack of height clearance at the subscriber unit (remote) and is consistent with the Proxim Tsunami MP.11a's specifications that optimal performance is obtained at the data-link rate of 36 Mbps.

6. Summary

From the field-testing conducted in a land environment, the following conclusions were made:

- A range of 2.35 km was achieved at the data-link rate of 36 Mbps.
- The maximum measured data throughput achieved at the data-link rate of 36 Mbps was approximately 10.85 Mbps.
- The optimal data-link rate was 36 Mbps.
- The file transfer at the data-link rate of 48 and 54 Mbps was either extremely slow (e.g., 0.48 Mbps) or could not be completed.
- Establishing a communication link at a higher data-link rate did not equate to a higher data throughput.
- The measured data throughput decreased with increasing range.
- The measured PER increased with increasing range.
- The average measured data throughput for 6, 9, 12, 18, 24 and 36 Mbps was 2.55, 4.67, 5.14, 7.45, 8.50 and 9.65 Mbps, respectively.

D. OVER-WATER ENVIRONMENT TESTING

1. Overall Performance Data

The performance data for the Proxim Tsunami MP.11a wireless system in an over-water environment is summarized in Table 24. The received signal strength, the maximum data-link rate, the maximum data throughput, and the average PER were measured and recorded at each test point. Compared to the Cisco Aironet 1400 wireless bridge, the Proxim Tsunami MP.11a had lower transmitted power and antenna gain. Therefore, only test points one and two registered a signal strength and field data.

An additional test point had to be used (test point 5), which was 250 m from the BSU, as no other vehicle-accessible test points could be found between 250 m and 1,750 m. The maximum data throughput of 10.65 Mbps was achieved at the data-link rate of 36 Mbps. Similar to the observations made in the land environment, the data throughput for the data-link rate of 48 and 54 Mbps were very low.

Test Point	Range (m)	Received Signal Strength (dBm)	Maximum Data-link Rate (Mbps)	Maximum Data Throughput (Mbps)	Average PER (%)
1	1,750	-80	24	8.54	0.33
2	2,700	-87	6	2.51	0.89
3	3,400	-	-	-	-
4	3,850	-	-	-	-
*5	250	-57	54	10.65	0.20

Table 24. Overall Measured Performance Data in a Water Environment (Proxim)

2. Received Signal Strength

Figure 50 shows the plot of the measured received signal strength versus range at all test points. The measured received signal strength decreased with increasing range.

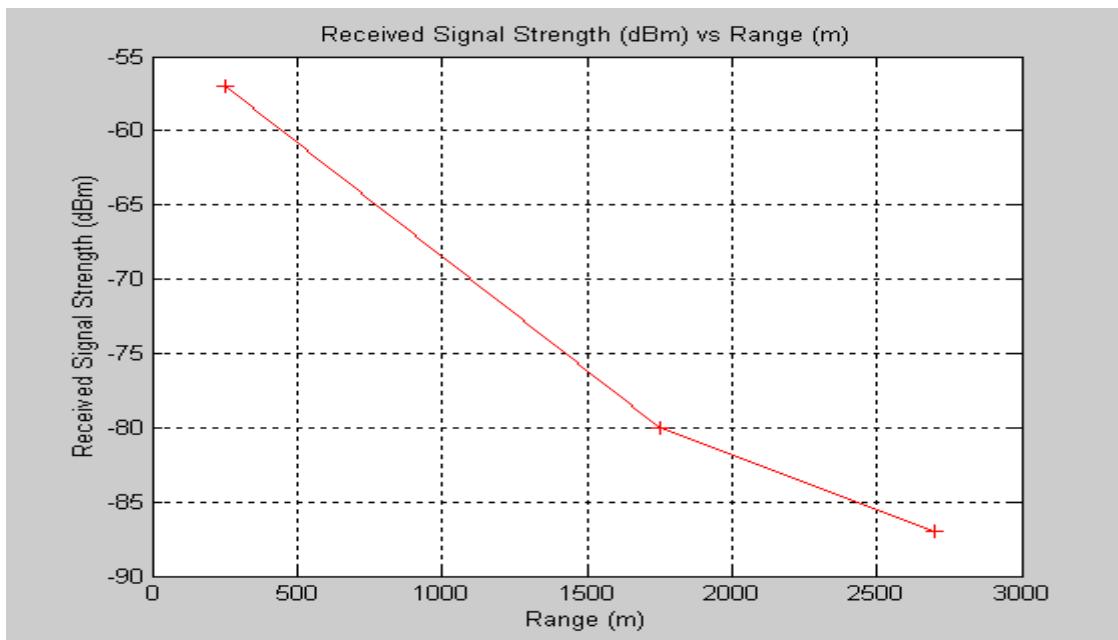


Figure 50. Measured Signal Strength at Receiver versus Range (Proxim – Water)

3. Optimal Data-link Rate

Figure 51 shows the plot of the maximum measured data-link achieved versus range at the three test points. Only test point one recorded a successful link establishment at the data-link rate of 54 Mbps. The optimal data-link rate was 36 Mbps.

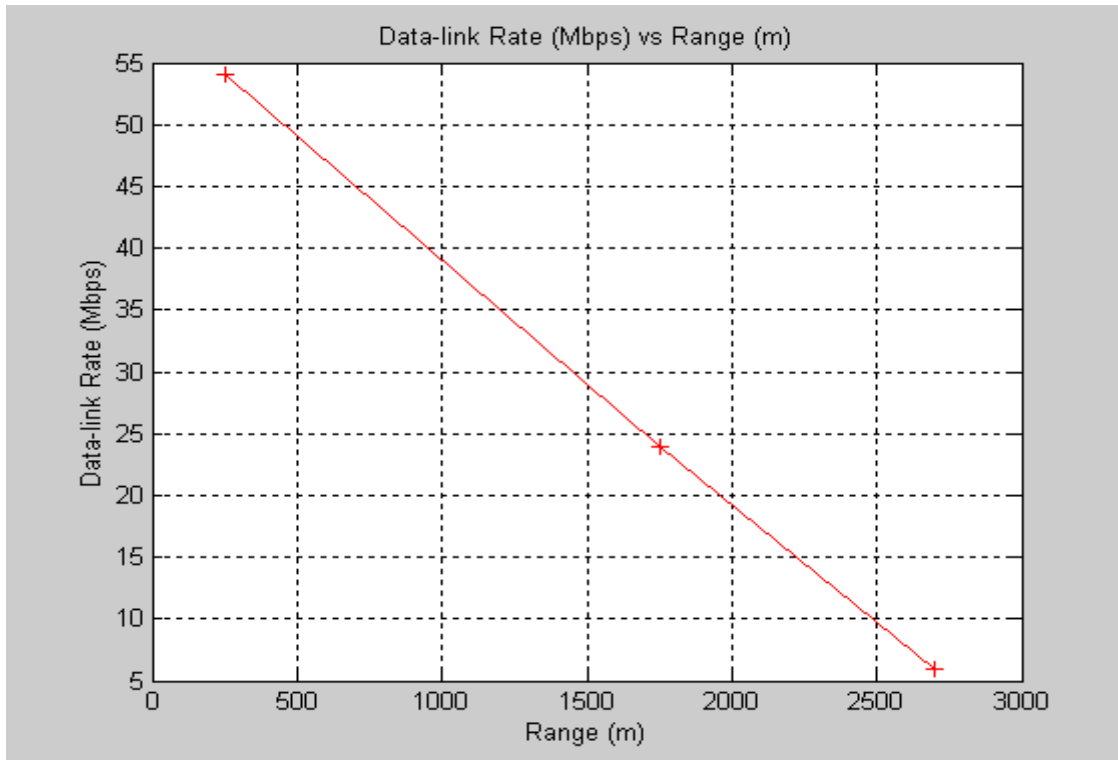


Figure 51. Maximum Measured Data-link Rate versus Range (Proxim – Water)

By varying the power setting, the field-testing showed that the receiver sensitivity was in accordance with its specifications (Table 7). The field data showed that the optimal data-link rate was 36 Mbps.

4. Maximum Data Throughput and Packet Error Rate

Figures 52 and 53 show the maximum measured data throughput and measured average packet error rate versus range at the three test points. Figure 52 shows the maximum data throughput decreasing with increasing range. This was consistent with the maximum data-link rate decreasing with increasing range. Figure 53 shows that the packet error rate increased with increasing range. The maximum measured data through-

put was achieved at the data-link rate of 36 Mbps. At this data-link rate, the packet error rate was very low and insignificant. At the higher data-link rate of 48 and 54 Mbps, the packet error rate was very high and the data throughput was very low.

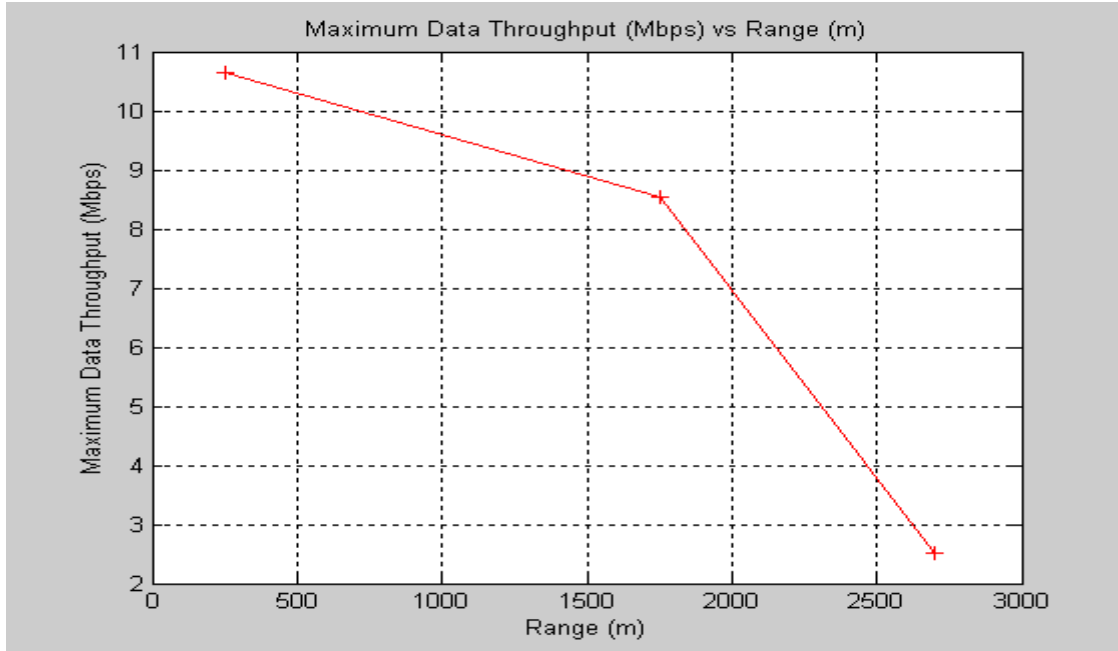


Figure 52. Maximum Measured Data Throughput versus Range (Proxim – Water)

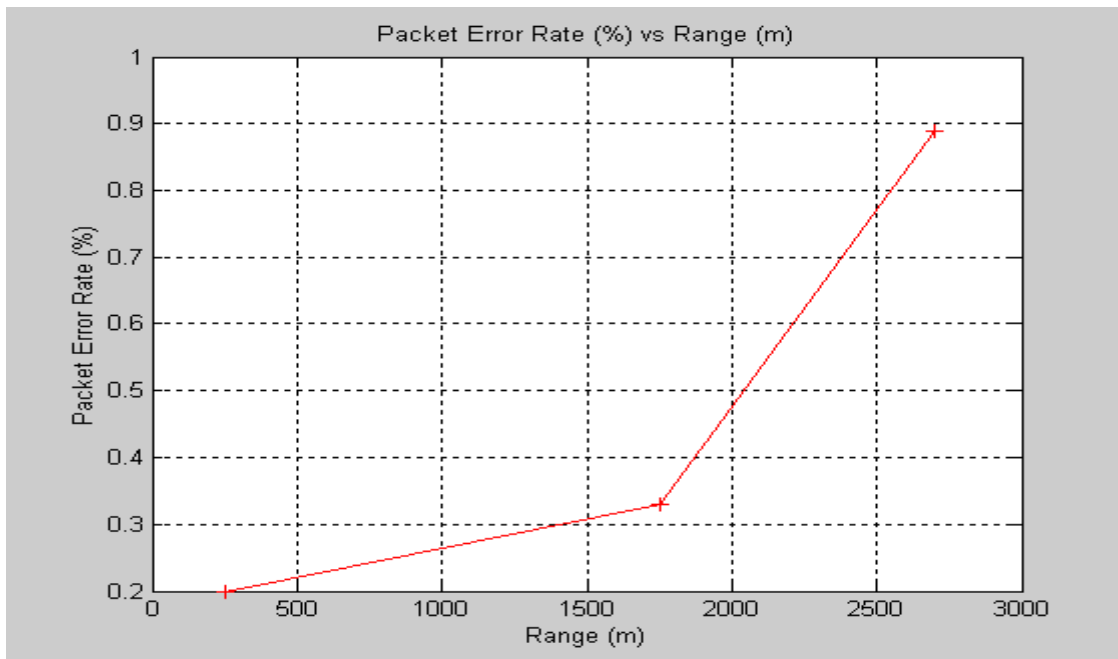


Figure 53. Measured Average Packet Error Rate versus Range (Proxim – Water)

5. Data Throughput versus Data-link Rate

Table 25 consolidates the measured performance data collected on the data throughput achieved over the entire range of the data-link rate (6 to 54 Mbps) at all three test points.

Test Point	Range (m)	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
		6	9	12	18	24	36	48	54
1	1,750	2.62	4.97	5.36	7.39	8.54	-	-	-
2	2,700	2.51	-	-	-	-	-	-	-
3	3,400	-	-	-	-	-	-	-	-
4	3,850	-	-	-	-	-	-	-	-
*5	250	2.72	5.09	5.49	7.51	8.69	10.65	-	-
Average Data Throughput		2.62	5.03	5.43	7.45	8.62	10.65	-	-

Table 25. Measured Data Throughput versus Data-link Rates at Various Ranges (Proxim – Water)

Figure 54 plots the measured data throughput achieved over the entire range of data-link rate (6 to 54 Mbps) at all three test points. Test Points one to three are plotted in red, blue and green, respectively. For the data-link rate of 48 and 54 Mbps, the data throughput was either very low or the file transfer could not be completed. The graph shows that data throughput degraded slightly as the distance increased. The average measured data throughput achieved for 6, 9, 12, 18, 24 and 36 Mbps was 2.62, 5.03, 5.43, 7.45, 8.62 and 10.65 Mbps, respectively. These values were higher than those obtained for the land environment.

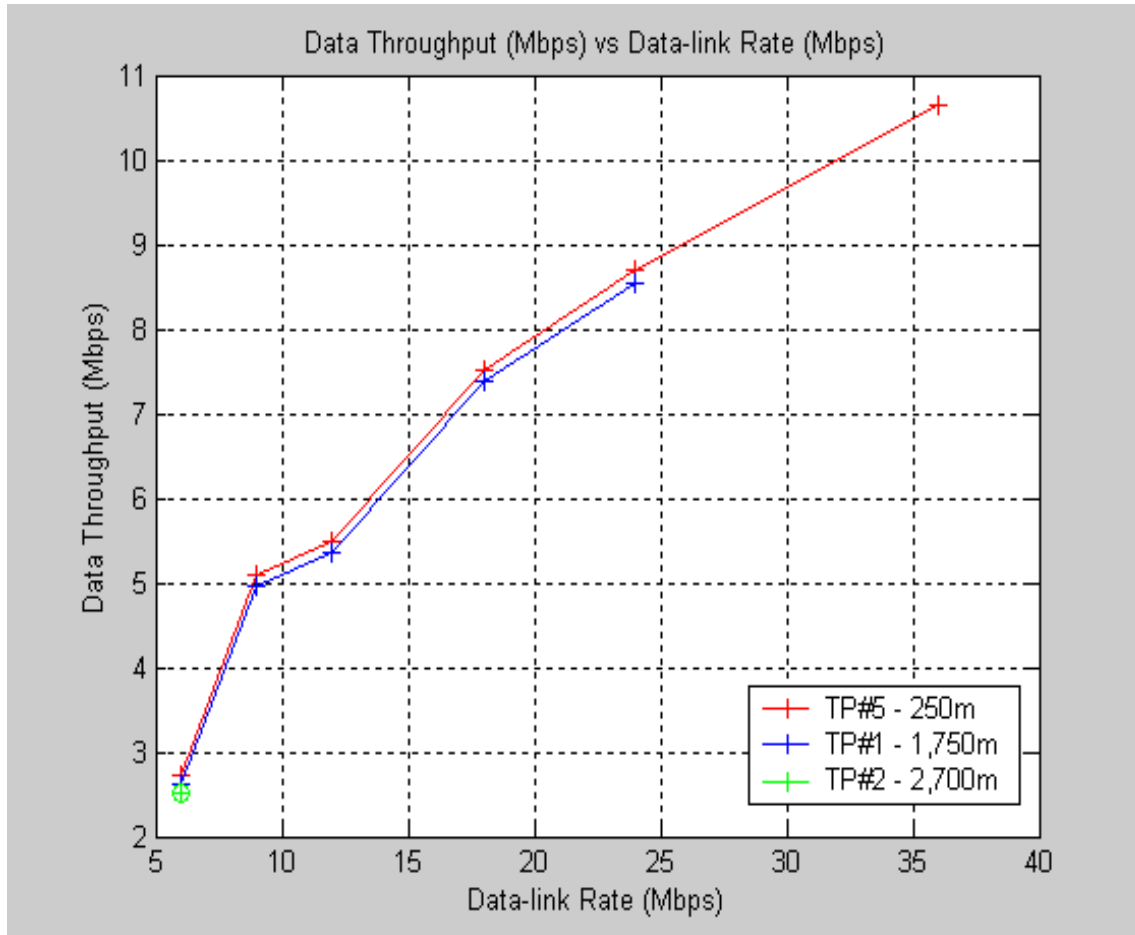


Figure 54. Plot of the Measured Data Throughput versus Data-link Rates at Various Ranges (Proxim – Water)

6. Summary

From the field-testing in a water environment, the following conclusions were made:

- The optimal data-link rate was determined to be 36 Mbps.
- Both data-link rates of 48 and 54 Mbps resulted in a high packet error rate and a very low data throughput. Most of the time, the file transfer was not successful at these higher data-link rates.
- Only test point five (additional test point at 250 m) achieved a communication link at the data-link rate of 36 Mbps.
- The maximum measured data throughput achieved at the optimal data-link rate of 36 Mbps was 10.65 Mbps.

- The receiver sensitivity at the respective data-link rate was in accordance with the specifications.
- The measured data-link rate and data throughput decreased with increasing range.
- The measured PER increased with increasing range.
- The average measured data throughput for 6, 9, 12, 18, 24 and 36 Mbps was 2.62, 5.03, 5.43, 7.45, 8.62 and 10.65 Mbps, respectively.

E. VEGETATION ENVIRONMENT TESTING

1. Overall Performance Data

The performance data for the Proxim Tsunami MP.11a wireless system in vegetation is summarized in Table 26. The received signal strength, the maximum data-link rate, the maximum data throughput, and the average PER were measured and recorded at each test point.

Test Point	Range (m)	Received Signal Strength (dBm)	Maximum Data-link Rate (Mbps)	Maximum Data Throughput (Mbps)	Average PER (%)
1	25	-63	54	10.86	0.04
2	50	-70	48	10.70	0.05
3	75	-74	36	10.38	0.09
4	100	-80	24	9.01	0.12

Table 26. Overall Measured Performance Data in Vegetation (Proxim)

2. Received Signal Strength

Figure 55 shows the plot of the measured received signal strength versus range at all test points. The measured received signal strength decreased with increasing range.

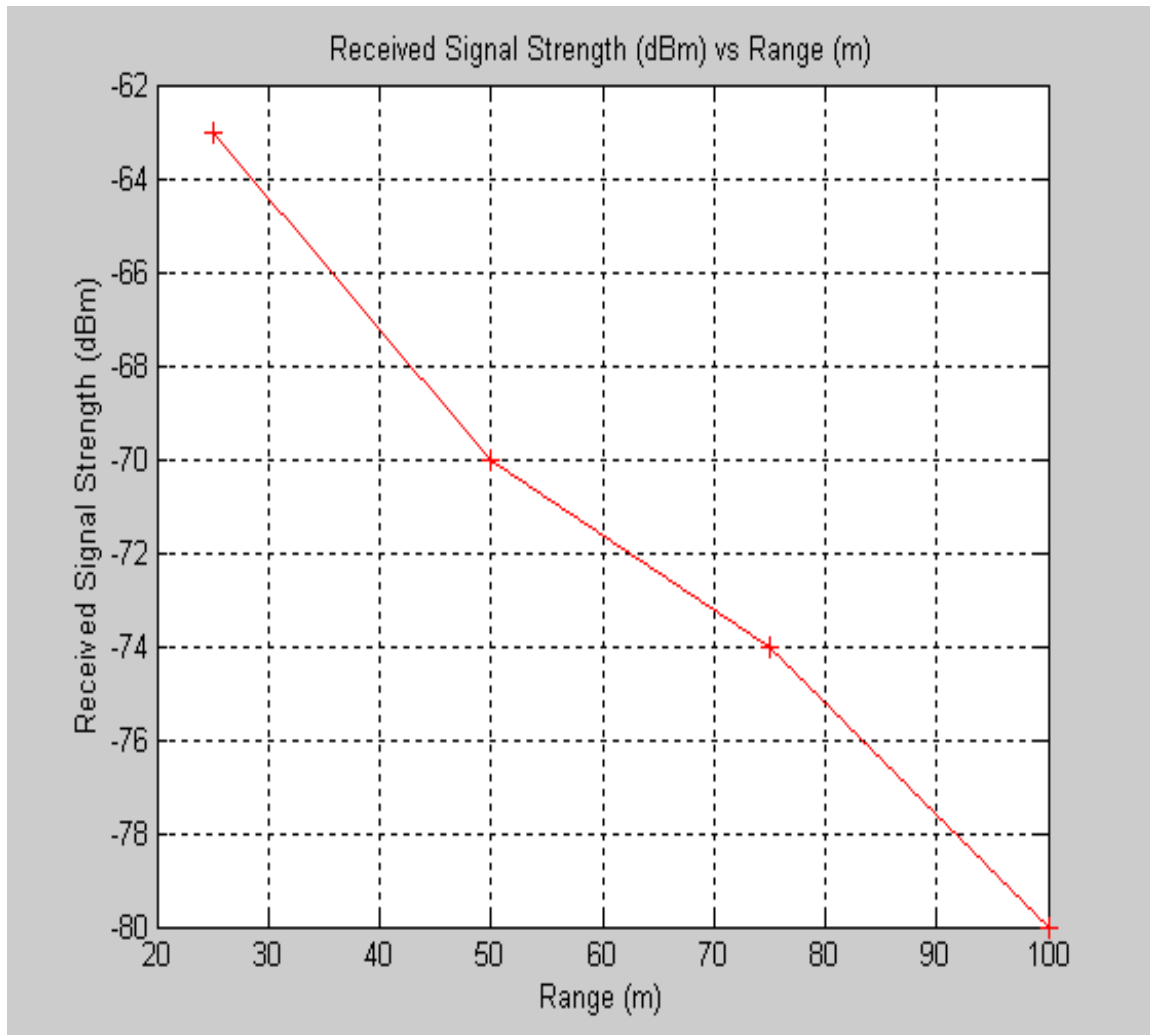


Figure 55. Measured Signal Strength at Receiver versus Range (Proxim – Vegetation)

3. Optimal Data-link Rate

Figure 56 shows the plot of the maximum measured data-link achieved versus range at the different test points. Consistent with the data recorded for the land and water environment, the optimal data-link rate was determined to be 36 Mbps.

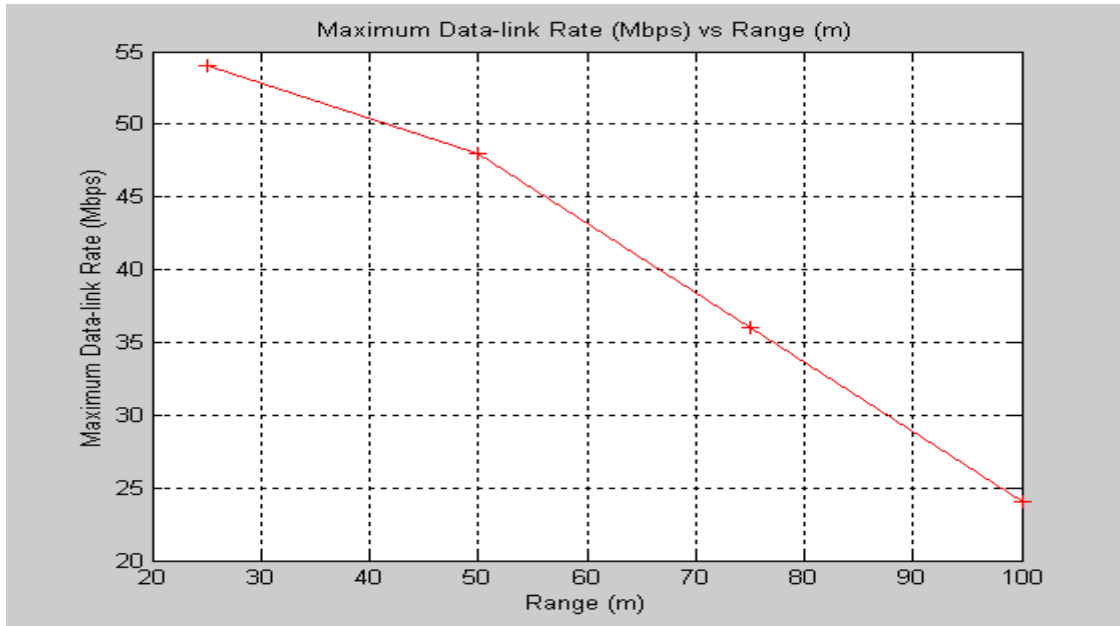


Figure 56. Maximum Measured Data-link Rate versus Range (Proxim – Vegetation)

4. Maximum Data Throughput and Packet Error Rate

Figures 57 and 58 show the maximum measured data throughput and measured average packet error rate versus range at all four test points. The maximum data throughput decreased with increasing range and the packet error rate increased with increasing range.

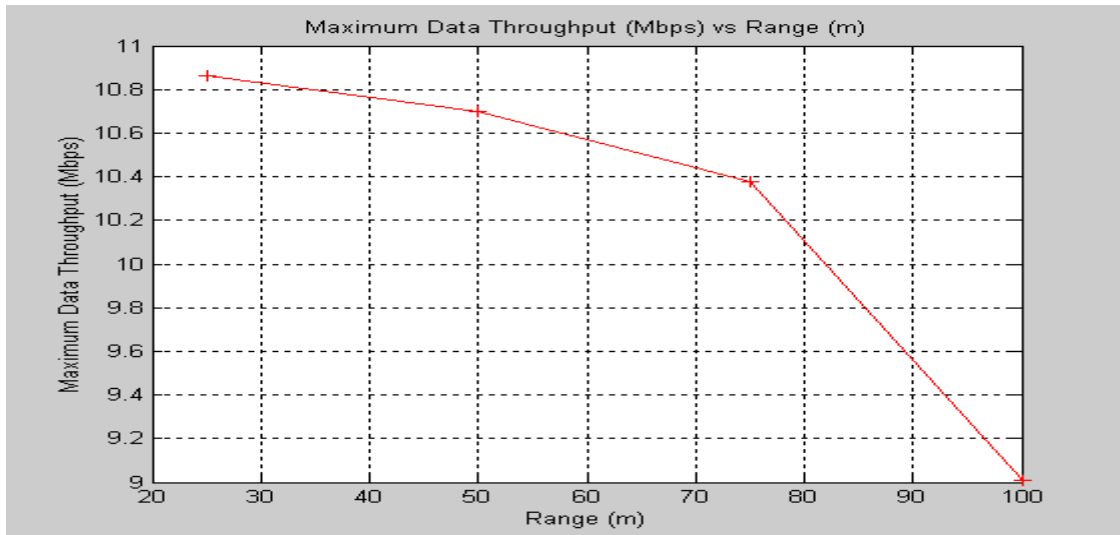


Figure 57. Maximum Measured Data Throughput versus Range (Proxim – Vegetation)

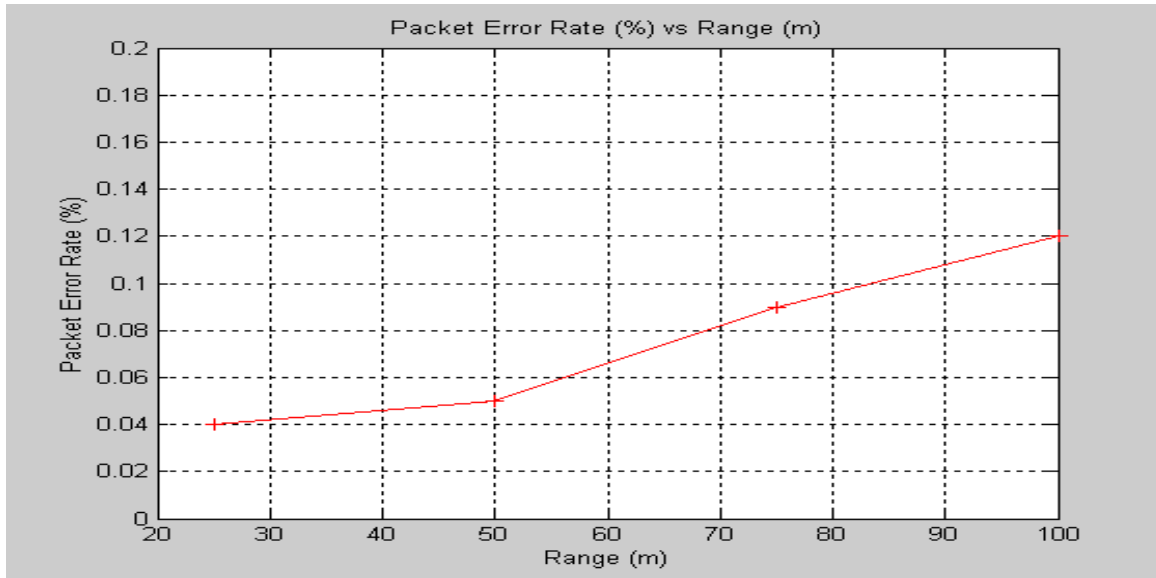


Figure 58. Measured Average Packet Error Rate versus Range (Proxim – Vegetation)

5. Data Throughput versus Data-link Rate

Table 27 consolidates the measured performance data collected on the data throughput achieved over the entire range of data-link rates (6 to 54 Mbps) at all four test points. Figure 59 plots the measured data throughput achieved over the entire range of data-link rates (6 to 54 Mbps). Test points one to four are plotted in red, blue, magenta and green, respectively.

Test Point	Range (m)	Data Throughput (Mbps) at Varying Data-link Rates (Mbps)							
		6	9	12	18	24	36	48	54
1	25	2.84	5.36	5.88	8.60	9.81	10.86	X	X
2	50	2.82	5.30	5.82	8.41	9.59	10.70	X	-
3	75	2.76	5.25	5.81	8.27	9.23	10.38	-	-
4	100	2.74	5.18	5.78	8.04	9.01	-	-	-
Average Data Throughput		2.79	5.27	5.82	8.33	9.41	10.65	-	-

Table 27. Measured Data Throughput versus Data-link Rates at Various Ranges (Proxim – Vegetation)

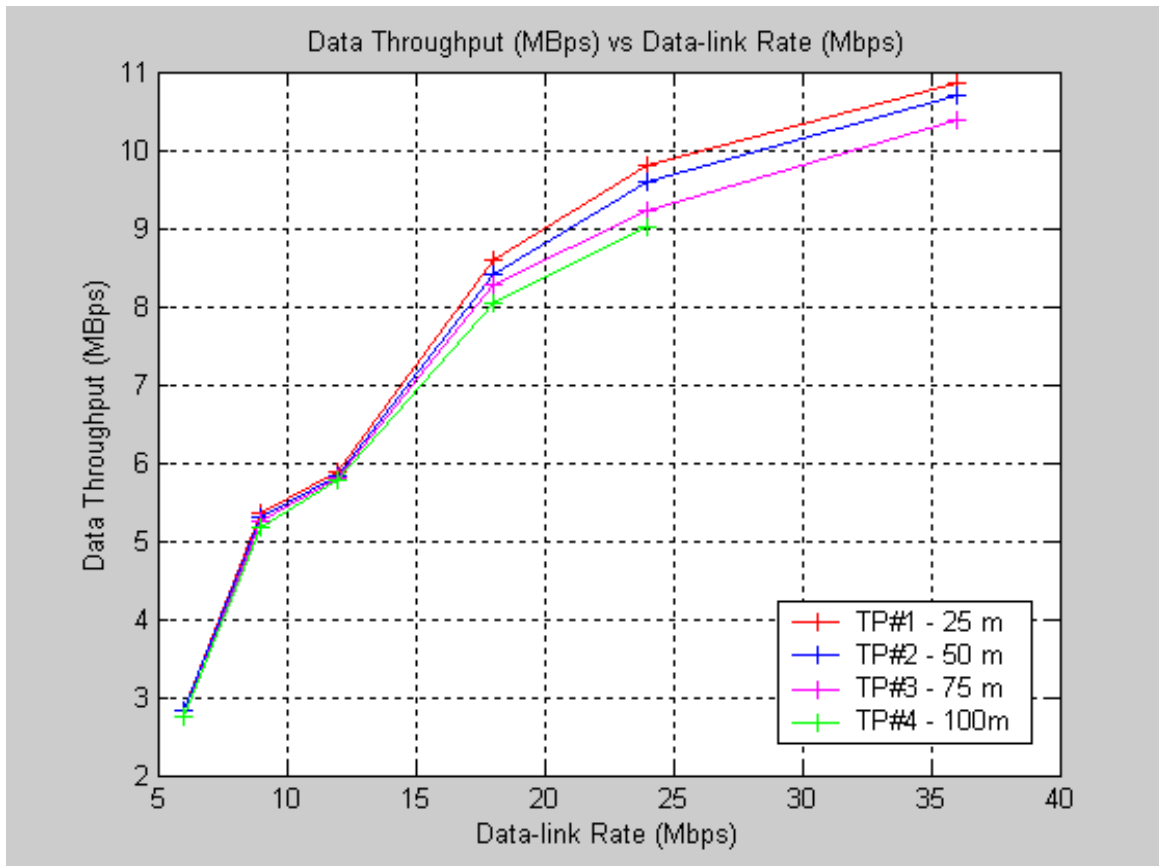


Figure 59. Plot of the Measured Data Throughput versus Data-link Rates at Various Ranges (Proxim – Vegetation)

Although communication links were established at 48 and 54 Mbps, the data throughput was very low and generally the file transfer could not be completed. The graph in Figure 59 shows that data throughput degraded with increasing distance. The average data throughput achieved for 6, 9, 12, 18, 24 and 36 Mbps was 2.79, 5.27, 5.82, 8.33, 9.41 and 10.65 Mbps, respectively.

6. Summary

From the field-testing in vegetation, the following conclusions were made:

- The optimal data-link rate was 36 Mbps.
- Both data-link rates of 48 and 54 Mbps resulted in a high packet error rate and a very low data throughput. Generally, the file transfer was not successful at these higher data-link rates.
- The maximum range achieved for the optimal data-link rate of 36 Mbps was 75 m.

- The maximum measured data throughput achieved at the optimal data-link rate of 36 Mbps was 10.86 Mbps.
- The measured data throughput decreased with increasing range.
- The measured PER increased with increasing range.
- The average measured data throughput for 6, 9, 12, 18, 24 and 36 Mbps was 2.79, 5.27, 5.82, 8.33, 9.41 and 10.65 Mbps, respectively.

F. CHAPTER SUMMARY

This chapter presented the laboratory setup and testing, the collection of data from the field-testing, and the performance analysis carried out for the Proxim Tsunami MP.11a wireless system. The signal attenuation, the Packet Error Rate (PER), and effective data throughput under all three operational environments – land, water, and vegetation – were investigated.

The next chapter presents the conclusion to this research and recommendations for future research.

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VII. CONCLUSION AND FUTURE WORKS

A. CHAPTER OVERVIEW

This chapter presents the conclusion to this research and recommendations for future research. The conclusion includes the performance analysis of both the Cisco Aironet 1400 wireless bridge and the Proxim Tsunami MP.11a wireless system in all three operational environments – land, water, and vegetation.

B. CONCLUSION

The objectives of this research were to answer the following questions:

- What specific commercially available low-cost hardware can be used to implement an IEEE 802.11a network outdoor?
- What is the performance capability of the hardware under various operational environments?
- How can the use of directional antennas improve the performance capability of the IEEE 802.11a network outdoors?

All the objectives identified at the beginning of this research were answered. Commercially available low-cost hardware was used to implement an IEEE 802.11a network outdoors – the Cisco Aironet 1400 wireless bridge and the Proxim Tsunami MP.11a wireless system. Both these products were chosen for their superior specifications and their company's reputation in the IEEE 802.11 wireless industry.

The performances of both these prototype systems were tested under three operational environments – land, water, and vegetation. From the field data collected, the following conclusions are made:

- The optimal data-link rate for the Cisco Aironet 1400 wireless bridge and the Proxim Tsunami MP.11a wireless system were 54 Mbps and 36 Mbps, respectively.
- At these optimal data-link rates, the average measured data throughputs were 20.38 and 10.78 Mbps, respectively.

- The receiver sensitivity for the Cisco Aironet 1400 wireless bridge was approximately 5 dB less than its specifications. The receiver sensitivity for the Proxim Tsunami MP.11a wireless system was in accordance with its specifications.
- The use of longer packet in the Cisco Aironet 1400 wireless bridge resulted in higher packet error rate. Despite this, the data throughput was not affected, as each packet was capable of transferring more data bits.
- For both prototype systems, the effect of the use of encryption (WEP or AES) on data throughput was negligible.
- The measured data throughput decreased and the measured packet error rate increased with increasing range. These observations were made for both systems.

To address the last question stated in the objectives, all tests were conducted using directional antennas. The ranges determined were much higher than those obtained using omni-directional antenna in Maj. Goh Che Seng's research [1].

Based on the performance data collected from field-testing, the Cisco Aironet 1400 wireless system outperforms the Proxim Tsunami MP.11a wireless system, especially in terms of data throughput performance. This conclusion stands even if the EIRP and antenna gain of the Proxim Tsunami MP.11a wireless system is increased to match that of the Cisco Aironet 1400 wireless bridge. On the other hand, the Cisco Aironet 1400 wireless bridge is more costly, heavier and consumes more power. This makes it more difficult to integrate onto military platforms.

The performance data shows that IEEE 802.11a is a viable option for the military to implement a high-speed LAN. As shown in this research, the range limitations of the higher frequency IEEE 802.11a can be resolved by using a smart directional antenna. The data throughput of approximately 20 Mbps meant that more users could be served in a cell, compared to the IEEE 802.11b. With the proliferation of IEEE 802.11a equipment, better chips with lower power consumption will likely emerge.

C. FUTURE WORKS

During the course of this research, several areas have been identified for future work. They are as follows:

1. Performance of IEEE 802.11a in a Mobile Environment

To implement a high-speed LAN successfully in the military, the effect of IEEE 802.11a equipment on moving platforms (UAVs, tanks, trucks, etc.) must be transparent to the user. The concerns are the Doppler effects and the handing-over/taking-over algorithm of switching base stations. The performance of the IEEE 802.11a in a mobile environment should be studied.

2. Maximum Number of Users per Base Station

The maximum number of users that can be supported by each base station and at a specific data throughput is another area for further study. This will determine the number of base stations that must be deployed in the area of operations.

3. Interference between Adjacent Frequency Channels

To exploit the frequency channels available to the IEEE 802.11a, adjacent frequencies must be used to increase the number of users within a cell. In theory, these frequencies are supposed to be orthogonal. Field-data could be collected to determine whether adjacent frequencies affect one another (especially using directional antenna), leading to a drop in the number of users within a cell.

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